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Ecological Risk Assessment for Kesterson Reservoir

Prepared for

U.S. Bureau of Reclamation

Mid-Pacific Region

December 2000

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Executive Summary

An Ecological Risk Assessment (EcoRA) was conducted for the terrestrial and ephemeral aquatic habitats of Kesterson Reservoir. The primary goal of the assessment was to add the results of ongoing monitoring activities to the EcoRA prepared in 1993 in order to update the characterizations of exposure and risk to Kesterson wildlife from selenium toxicity. The secondary goal was to evaluate the results of the EcoRA with respect to management strategies and the environmental monitoring program, and to make recommendations to optimize future management of the habitat.

The EcoRA summarized existing data to develop predictive relationships between annual climatic regime and exposure of wildlife to Kesterson Reservoir's selenium inventory. Ephemeral pools were of particular interest because monitoring has revealed relatively high waterborne and aquatic invertebrate selenium concentrations in the pools. Consequently, there is a potential risk of exposure for semi-aquatic birds that feed at Kesterson during their nesting seasons if the pools persist long enough. Risks were assessed using a standard EcoRA framework. Data that were summarized and used in conjunction with models for the risk assessment include:

- Soil selenium concentrations
- Water-extractable soil selenium concentrations
- Terrestrial plant, invertebrate, bird, and mammal tissue selenium concentrations
- Bird egg selenium concentrations
- Ephemeral pool waterborne selenium concentrations
- Ephemeral pool aquatic invertebrate tissue selenium concentrations
- Daily bird use data for semi-aquatic birds considered in the EcoRA
- Long-term historical precipitation and evapotranspiration data for the Kesterson area
- Aerial photographic records of the extent of ephemeral pools at Kesterson Reservoir in the winter and spring months

A conceptual model was constructed to provide a framework for the risk assessment that included descriptions of the physical, chemical, and ecological settings, assessment endpoints, and measures used to assess risk. Model analyses used Monte Carlo simulations of 1,000 years of naturally varying climatic regime to predict future exposures to selenium levels that may cause toxic effects.

Water-extractable selenium in the soil was used as a predictor of exposure to plants and the terrestrial food chain, as well as to waterborne selenium in the ephemeral pools. The models predicted the average dietary or tissue concentrations for various bird and mammal species. In the case of semi-aquatic birds, predicted occurrence of ephemeral pools, based on climatic regime, was a critical determinant of exposure to selenium from the pool pathway. From

knowledge of average dietary concentrations, risks of toxicity from selenium could be assessed for receptor birds and mammals based on known dietary transfer factors and literature values identifying potentially toxic concentrations of selenium in diet, tissue, blood, or eggs.

The EcoRA models predicted minimal risk of selenium toxicity through terrestrial or aquatic food chains at Kesterson Reservoir. The terrestrial habitats model predicted minimal risk of selenium toxicity at Kesterson. Combined dietary concentrations were less than toxicity levels, with the possible exception of diet for loggerhead shrike. Risks were variable by annual climatic regime for aquatic exposure. Monitoring data over the last 12 years have not revealed evidence of reproductive toxicity to terrestrial or semi-aquatic birds at Kesterson Reservoir.

Although ephemeral pool water and aquatic invertebrate selenium concentrations at Kesterson are usually elevated to levels of concern for adverse effects, ephemeral pools do not form in most years or they are of insignificant duration. As a consequence, bird use of, and exposure from, the pools is very limited. The aquatic habitats EcoRA model predicted that it is likely that only one or two birds of semi-aquatic species (such as black-necked stilt, killdeer, or mallard) may be affected by selenium-related reproductive impairment, and this would occur in less than 5 percent of the years.

The major conclusions were that (1) there is no evidence for long-term change in the soil selenium inventory or its bioavailability, and (2) current risks to terrestrial and aquatic wildlife are limited and climate-dependent (for aquatic exposure). It is recommended that (1) low-lying areas of Kesterson Reservoir in which ephemeral pools form on an annual basis due to rising groundwater be filled, (2) monitoring of selenium in biota, soil, and water be continued at 5-year intervals, with additional monitoring of ephemeral pools during very wet years, and (3) the site continue to be managed as terrestrial open-space habitat, with provision for long-term management and monitoring by an academic, non-profit, or other entity that will allow for continued study of the site.

SECTION 1

Introduction

1.1 Site Background

1.1.1 Location

Kesterson Reservoir is located in the Grasslands area of northern Merced County, within the San Joaquin Valley of California. Figure 1-1[a] shows a map that includes the location and configuration of the subdivided "ponds" of the Reservoir structure, as well as the three main habitat types (explained in Section 2.2.1).

1.1.2 History

The Reservoir was constructed between 1968 and 1975 as a series of 12 shallow ponds totaling approximately 500 hectares (1,200 acres) that served as a disposal site for subsurface agricultural drainage. Drainage collection systems collected shallow saline groundwater from fields in Fresno County and conveyed it to the Reservoir via the concrete-lined San Luis Drain. Following the discovery of selenium contamination in Kesterson Reservoir, the U.S. Bureau of Reclamation (USBR) halted discharge of agricultural drainage to Kesterson, dewatered the Reservoir, and filled lower-elevation portions to prevent groundwater from rising to the ground surface. A further description of the site and its early history are provided by USBR, et al. (1986), the U.S. Department of the Interior (USDI, 1989), and Ohlendorf (1989).

Biological monitoring of Kesterson Reservoir has been conducted annually since 1988. The objectives of the monitoring program were defined as follows by the Central Valley Regional Water Quality Control Board's Order No. 88-7:

- Assess the impact of Kesterson Reservoir on local and migratory wildlife.
- Provide a basis for adjusting Kesterson Reservoir management.
- Verify the effectiveness of cleanup actions at Kesterson Reservoir.
- Provide a basis for modifying future biological monitoring.

The monitoring initially included habitat mapping; vegetation, invertebrate, and soil sampling and analyses; bird censusing; bird nesting surveys and reproduction analyses; bird, reptile, amphibian, and small mammal collection and analyses; and night surveys of wildlife. The monitoring program subsequently was changed to incorporate on-site or laboratory studies to provide more specific information on particular topics. This EcoRA uses the results of the monitoring and site-specific studies, as well as related information, to assess risks to wildlife associated with selenium exposure at the Reservoir.

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[a] All figures are included at the end of the report.

1.1.3 Previous Investigations

1.1.3.1 Physical and Chemical Investigations

Beginning in 1983, a series of investigations documented the nature and occurrence of selenium contamination in soils, surface water, and groundwater at Kesterson Reservoir. Early investigations focused on surface water and the physical/chemical processes associated with selenium bioaccumulation in the aquatic food chain. These studies demonstrated that while selenate was the predominant form of selenium in surface waters, the pond bottom sediments accumulated high concentrations (tens to hundreds of mg/kg) of selenium in the elemental and organically associated forms. This accumulation resulted from a combination of microbial transformation of selenate to elemental selenium in the pond-bottom sediments and decomposition of aquatic vegetation such as the macro-algae chara and cattails (Weres, et al., 1989; Oremland, et al.,1989; Horne and Roth, 1989).

In 1988, with the drying out of Kesterson and filling of low-lying areas, studies shifted to focus on the upland environment and the ephemeral pools that form during the rainy winter months. Specific investigations related to the physical and chemical behavior of selenium in the Kesterson environment include:

- **Spatial Distribution and Time Trends in Soil Selenium Concentrations**
    - Selenium speciation and fractionation investigations showing the depth distribution of elemental selenium, selenate, selenite and organically associated selenium at numerous sites throughout Kesterson (Weres, et al., 1989; Tokunaga, et al., 1994)
    - Long-term monitoring of the depth distribution of extractable and total selenium concentrations at several sites from 1988 through 1998 (Tokunaga, et al., 1994; Zawislanski, et al., 1992)
    - Synoptic measurements of total and water-extractable selenium concentrations at 54 locations across Kesterson from 1990 to 1998 in conjunction with the biological monitoring program (Wahl, et al., 1994; for summary see Zawislanski, et al., 1999)
    - Field-measured volatilization rates from several experimental plots (Frankenberger and Karlson, 1995; Zawislanski, et al., 1996)
    - Laboratory measurements of selenium re-oxidation rates under controlled conditions (Zawislanski and Zavarin, 1996; Dowdle and Oremland, 1998; Losi and Frankenberger, 1998)
    - Modeling studies of the above-mentioned data to determine re-oxidation and leaching rates of selenium (Benson, et al., 1992; Wahl and Benson, 1996)
- **Ephemeral Pool Occurrence and Selenium Concentrations**
    - Field measurements of selenium concentrations in ephemeral pools from 1992 through the present (see summary Zawislanski, et al., 1999; CH2M HILL, 2000)
    - Field observations of the inception and duration of ephemeral pools from 1990 through the present (Zawislanski, et al., 1999)

- Development of a model relating inception and duration of ponding to the difference between precipitation and cumulative evapotranspiration (Zawislanski, et al., 1999)
- Aerial photographs taken early to mid-spring showing the location and extent of ephemeral pools
- Laboratory studies elucidating the physical and chemical processes contributing to intra-annual trends in selenium concentrations in ephemeral pools (Tokunaga, et al., 1997, 1998)
- Kesterson Reservoir Biological Monitoring (e.g., CH2M HILL, 1999a)

Together these studies have been sufficient to develop an understanding of the current status of selenium in soils and ephemeral pools at Kesterson and how these are likely to evolve over time. Today, much like in 1988, most of the selenium is confined to the top 15 cm of soil. Only a small fraction of the selenium in surface soils, typically less than 5 percent, is currently in extractable or mobile forms (that is, as dissolved selenate and selenite). This situation changes on a year-to-year basis as a result of a combination of re-oxidation of the immobile pools of selenium, leaching from rainfall, periodic reduction when anoxic conditions are established in the soil profile, and, to a lesser degree, because of volatilization. Re-oxidation acts to increase the extractable selenium in surface soils at a rate of less than 5 percent per year (and as will be discussed later in the report, recent analysis suggests rates of 1 to 2 percent per year). Depending on the amount and timing of rainfall, leaching carries surface selenium deeper into the soil profile. Periodic anoxia in the soil profile during and following periods of extensive precipitation converts selenate and/or selenite to more reduced forms, which become part of the immobile pool of selenium. Volatilization converts a small fraction of the selenium (less than 1 percent per year) to methylated forms of selenium that are dissipated in the atmosphere. Over the long term, the net effect of these processes will be to deplete the total and extractable surface selenium inventory. However, this process will be slow, as confirmed by the lack of a statistically significant decrease in either the total or extractable selenium inventory from 1990 to 1998 (Zawislanski, et al., 1999).

Ephemeral pools at Kesterson are formed primarily by the accumulation of rainwater on the soil surface. When the cumulative amount of precipitation exceeds the cumulative evapotranspiration, pools form and then persist until the water is evaporated. Selenium concentrations in these pools range from 1 to about 3,000 μg/L. The highest selenium concentrations occur immediately after the pools have formed; then they decrease to relatively stable concentrations in the range of 1 to 200 μg/L after several weeks. The selenium in these pools results from dissolution of salt crusts and diffusion of dissolved selenium from pore waters into the overlying surface waters. Once the pool is formed, anoxic conditions may develop in the underlying soils. Over time, diffusion of selenium from the pools back into the underlying soils depletes the concentration of selenium in surface water. Simultaneously, selenium diffused back into the soils is reduced to immobile forms. Again, as demonstrated by nearly a decade of monitoring, the net effect of these processes is that we expect selenium concentrations in ephemeral pools to remain in the current range for several decades.

1.1.3.2 Ecological Investigations

A series of field and laboratory studies, beginning in 1983, documented the bioaccumulation of selenium in food-chain organisms and its adverse effects on aquatic birds feeding at Kesterson (summarized by Ohlendorf, 1989). These birds exhibited high rates of embryo deformities and mortality, as well as adult bird mortality. In contrast, studies of mammals and terrestrial birds using Kesterson showed significant levels of selenium bioaccumulation, but no clear evidence of adverse effects. These findings, among others, contributed to the decision to dewater the Reservoir and fill low-lying areas as a means of site remediation.

Selenium monitoring and several focused studies have been conducted at Kesterson since 1988 to determine temporal and spatial trends in selenium levels and to determine whether existing conditions cause adverse effects in wildlife (see, for example, CH2M HILL, 2000). Although selenium concentrations are elevated in all environmental media (soils, plants, and animals), the monitoring has not found evidence of embryo deformities, reduced egg viability, or wildlife mortality.

An ecological risk assessment (EcoRA) was conducted in 1993 to: (1) review pertinent information available at that time, (2) estimate future levels of selenium in various biota (plants and animals) at Kesterson, (3) estimate the risks to animals caused by the site's selenium inventory, (4) assess the significance of the site's selenium toxicosis risks, (5) identify contingency plans and evaluate their effectiveness in eliminating or reducing any potentially significant risks of selenium toxicosis, and (6) recommend research and monitoring that would provide information needed to improve management efficiency for Kesterson or other projects (CH2M HILL, 1993; Ohlendorf and Santolo, 1994).

That risk assessment analyzed data available from the Kesterson Reservoir Biological Monitoring Program through November 1992, as well as other published and unpublished reports. Total and water-soluble selenium concentrations in the top 15 cm of soil, along with selenium concentrations in a wide range of plants and animals, were used to model potential exposures and to predict effects to terrestrial wildlife over a period of 20 years into the future. In addition, waterborne selenium concentrations and selenium in aquatic invertebrates from ephemeral pools were used to evaluate potential risks to aquatic birds.

The overall conclusions of the risk assessment were that: (1) selenium concentrations in the plants and animals using Kesterson were not expected to change markedly during the next 20 years, (2) the selenium concentrations in small mammals were expected to remain below those measured during a study in 1984 when the Reservoir was partially flooded with drainwater (and there were no clear effects on small mammal reproduction; Clark, 1987), (3) selenium concentrations in insectivorous birds were not expected to increase to biologically significant levels, (4) the greatest risk of selenium exposure to terrestrial wildlife appeared to be the possible consumption of mushrooms that contain the highest levels of selenium found at Kesterson (but there was little evidence that birds or mammals ate the mushrooms), (5) much of the Reservoir could be covered with standing water during very wet years as a result of pooling of rainwater, and (6) although selenium concentrations in these pools (water and biota) are lower than pre-1989, aquatic birds may feed in pools that persist into spring and may be exposed to selenium at levels that could cause adverse reproductive effects.

Based on the conclusions of the risk assessment, no active site management of terrestrial habitat was proposed unless further information was obtained that indicates a significant threat of selenium toxicosis to wildlife. The assessment concluded that biological monitoring should be continued to assess whether adverse effects were likely to occur in wildlife, but the monitoring program could be modified by decreasing the number of analyses for most plants and animals. Consequently, the monitoring program was modified in 1995, changing from annual comprehensive monitoring to more focused annual monitoring of selected biota that were judged to be at highest risk, with more comprehensive sampling of biota every 3 years. In addition, several focused field and laboratory studies were undertaken to further evaluate risks to particular species (such as raptors); these are summarized in the annual monitoring reports (such as CH2M HILL, 2000, and previous reports).

It appeared that no further actions were warranted for management of ephemeral pools during dry years, because these pools disappear soon after the rainfall ends. However, management actions were recommended in the event that rainfall is higher than normal during late winter or early spring (as occurred in 1998 and some other years). Monitoring of these pools has been included each year during late winter and early spring (CH2M HILL, 2000).

1.2 Objectives

Since completion of the previous EcoRA (CH2M HILL, 1993; Ohlendorf and Santolo, 1994), biological as well as abiotic monitoring has continued at Kesterson and no deaths or deformities from selenium toxicosis have been observed in wildlife. The overall goal of the current project is to add the results of monitoring conducted since the 1993 risk assessment and to evaluate the success of management strategies. A secondary goal is to ascertain whether the intensity of current site management and monitoring is appropriate for the risk. Specifically, the objectives of this assessment are to:

- Assess the risks to wildlife from the site's selenium inventory, based on observed and estimated levels of biologically available selenium,
- Develop contingency plans for controlling the routes of exposure and risk identified in the assessment, and
- Recommend appropriate monitoring for Kesterson and additional research (if any) that would provide information needed to improve management efficiency for Kesterson and/or other projects.

The basic approach of this study was to assess risks to wildlife using a standard EcoRA framework, similar to that outlined in U.S. Environmental Protection Agency (USEPA) guidance (USEPA, 1998). The primary method of risk determination was to estimate the variability in risk as provided by the natural variation in annual climatic regime. In all cases Kesterson physical, chemical, and biological monitoring results formed the basis for risk estimates.

SECTION 2

Problem Formulation

The problem formulation section presents information that was used to develop and focus the Analysis phase of the EcoRA by describing the ecological characteristics of Kesterson Reservoir, summarizing previously existing data, and specifying the goals of the assessment. The end products of the problem formulation are an ecological conceptual site model and an analysis plan that describe the potential ecological receptors (such as wildlife species) that may be affected at the site, the chemicals of potential ecological concern (COPECs), the important aspects of the site to be protected (referred to as "assessment endpoints"), the means by which the assessment endpoints will be evaluated (called "measures"), and the approach used for conducting the analyses. The following information was used to develop the conceptual site model and analysis plan:

- Physical Setting - provides a general description of the climate, hydrology, and selenium speciation at Kesterson
- Ecological Setting – provides a description of the terrestrial and aquatic habitats and typical plants and animals at Kesterson and also includes a list of the receptors chosen for analysis
- Chemicals of Potential Ecological Concern – provides a brief description of contamination at the site and identifies selenium as the COPEC for evaluation in this EcoRA
- Assessment Endpoints and Measures – provides a description of the assessment endpoints (or important resources to be protected at the site) and measures (predictors of the assessment endpoints and the means by which the risks will be estimated)

2.1 Physical Setting

2.1.1 Climate and Hydrology

The Kesterson area has a semi-arid, Mediterranean climate typical of its location in the western region of Merced County. The wet season months, November through May, receive more than 95 percent of the mean annual rainfall (226 mm), and have relatively low pan evaporation rates. The hot, dry months of June through September have average temperatures ranging from 19 to 26° C. More detailed weather data, with emphasis on wet season months, are presented in Section 2.6.1.

Ephemeral pools formed by ponding rainwater reflect conditions where seepage rates into soils lag behind "net" rainfall (rainfall minus evapotranspiration). As a result, primary factors controlling ephemeral pool formation at Kesterson Reservoir are rainfall, evapotranspiration, soil permeability, and the soil profile hydraulic potential gradient.

Field-saturated hydraulic conductivity measurements of surface soils at Kesterson Reservoir have shown that permeabilities typically are moderately low to low. Luthin (1966) reported a

value of 30 mm per day from infiltrometer measurements at Kesterson, without mention of the number of measurements. Surface soil hydraulic conductivities from 20 infiltrometer measurements performed on Waukena soils (now mapped as members of the Turlock soil series) at Kesterson ranged from 0.8 mm up to 42 mm per day, with an arithmetic average of 13 mm per day (Jackson, 1967). Harmonic mean values of soil profile hydraulic conductivities range from 2 to 44 mm per day, and the arithmetic mean of these 8 harmonically averaged profile values is 12 mm per day (Lawrence Berkeley Laboratory, 1987). There are locations within Kesterson Reservoir where surface soils have higher-than-average clay and silt contents, so they have significantly lower saturated hydraulic conductivities. The harmonic mean profile averaged saturated hydraulic conductivity at one of these sites (P8EP) is 1 mm per day (Zawislanski, 1989).

The wet season at Kesterson Reservoir coincides with months during which the shallow groundwater rises to nearly reach the soil surface. Under post-closure, pre-fill conditions, much of the area was topographically low enough to permit surfacing of the groundwater during winter months. This type of groundwater-supported ephemeral pool formation can be practically independent of rainfall. The recognition that Kesterson ephemeral pools formed by groundwater rise were extremely seleniferous (Tokunaga and Benson, 1992) led to the filling of topographically low areas with additional soil (USDI, 1989). Currently, only a very small portion (< 1 percent) of Kesterson Reservoir exhibits this mode of pooling, and the vast majority of current ephemeral pools form by ponding of rain water. However, the seasonally very shallow depth to the water table continues to have two important hydraulic influences in these larger areas at Kesterson. First, the available water storage capacity (that is, the air-filled pore volume) of Kesterson soil profiles during the wet season is low. Average air-filled porosities of these soils are approximately 0.1 when the water table is at a depth of 1.0 meter. Second, hydraulic head gradients within soil profiles become very small (typically less than 0.04 m/m) during ponding so that the seepage rate (product of hydraulic conductivity times the hydraulic head gradient) also is small.

The present risk analysis is based on the assumption that climatic and hydrologic conditions remain within a range defined by the record compiled over the last century. This includes the expectation that neither rainfall nor evaporation rates will change significantly over the next few decades. It also assumes the stability of other factors, such as regional climate, regional and local groundwater use, and flooding of surrounding areas for waterfowl habitat. Although one cannot predict long-term climatic changes, past groundwater level records (1970-2000) indicate the absence of trends on this time scale. The flooding of duck clubs to the west and south of the Reservoir has been ongoing throughout the existence of Kesterson Reservoir. Flooding depth and duration are controlled by the existing topography, waterfowl habitat requirements, and water availability. As a result, the wintertime conditions established at the duck clubs have been more or less stable and are not expected to change. The effects of the flooding of land to the east of the Reservoir during the late 1990s have been observed in changes to the shape of the groundwater surface in the southern and eastern Kesterson ponds. A close examination of the groundwater data indicates that these effects are minor and do not influence the formation of ephemeral pools away from the eastern boundary of the Reservoir. The development of the Freitas Unit of the San Luis National Wildlife Refuge has been completed and further major hydrologic changes are not anticipated. A detailed examination of long-term regional and more recent local groundwater trends is presented in Appendix A.

Concerns about the off-site migration of Kesterson Reservoir groundwater prompted the installation of a number of monitoring wells in the downgradient direction. Boron and selenium trends in groundwater from these peripheral monitoring wells are indicative of a very slow-moving plume. Continuous records have been collected from these wells over the past 10 to 12 years. In some cases, the direction of groundwater flow has been changed, such that boron concentrations have decreased in wells near the eastern boundary of the site. This is due to the presence of maintained wetlands in the adjacent Freitas Unit over the last 5 years. Under present hydrologic conditions, sampling of groundwater on a 5-year interval is considered adequate to capture the plume movement, if any should occur. Groundwater quality data are presented and further discussed in Appendix A.

2.1.2 Selenium Speciation

Selenium bioavailability and mobility are controlled by selenium speciation. When first introduced to Kesterson Reservoir, selenium was in its most oxidized state of selenate [Se(VI)], which is most mobile given its high solubility and low sorption. Subsequently, selenium was largely reduced under ponded conditions and very little (less than 5 percent) of selenium is currently found as Se(VI). More chemically reduced and less-soluble species [elemental selenium, organically associated selenium, and selenite, Se (IV)], have since dominated. These species can all be oxidized to Se(VI), and both elemental selenium and organo-selenium can be oxidized to Se(IV). Long-term monitoring has shown that selenium may be seasonally re-oxidized, but tends to be reduced during wet months (Zawislanski, et al., 1996). Since selenium reduction is far more rapid than oxidation (Zawislanski and Zavarin, 1996; Losi and Frankenberger, 1998), the average selenium oxidation state does not change significantly from year to year. The net result is a stable set of species, with roughly equal fractions of elemental selenium, organo-selenium, and Se(IV), with minor Se(VI).

The uptake of selenium by plants is limited by soluble selenium concentrations. Despite its high solubility, Se(IV) sorbs strongly onto iron oxides (Hamdy and Gissel-Nielsen, 1977), clay minerals (Bar-Yosef and Meek, 1987), and soil organic matter (Yläranta, 1983). Generally, 2 to 10 percent of total selenium remains in the soil solution of near-surface soils (Tokunaga, et al., 1991; Zawislanski and Zavarin, 1996). At Kesterson, that translates to an average soluble selenium concentration around 0.1 to 1 mg/kg (Zawislanski, et al., 1999).

The long-term trend of selenium speciation changes will be toward more oxidized species. Selenium will also tend to be redistributed with depth. The rate at which these shifts will occur depends on weather patterns, primarily rainfall intensity and timing. Based on data collected during the 1990s, these changes were so slow that they were generally not quantifiable over that time period (Zawislanski, et al., 1999). It will be shown in subsequent sections that soil selenium concentrations and soluble selenium levels may be assumed constant over the next 10 years or longer.

2.2 Ecological Setting

The purpose of this section is to describe the biotic and abiotic aspects of the ecological setting of Kesterson Reservoir relevant to the EcoRA. Various representative plant and animal species at Kesterson Reservoir must be chosen as ecological "receptors" of potential

selenium exposure. In addition, habitats are described and information on selenium concentrations in various media is summarized in relation to the EcoRA process.

2.2.1 Terrestrial Habitats

The drying and filling of the Reservoir converted the predominantly wetland habitat to upland habitat of three types (Ohlendorf and Santolo, 1994) (Figure 1-1). *Filled* habitat includes the formerly low-lying areas that were filled with soil to prevent the occurrence of seasonal wetlands; it covers approximately 60 percent of the site. *Grassland* habitat (which covers approximately 30 percent of the site) includes the higher-elevation, upland area that existed within the site before it was dried and filled. *Open* habitat (approximately 10 percent of the site) includes areas that were not filled, but where cattails were disked to prevent use by tricolored blackbirds (*Agelaius tricolor*).

The plant species composition, in terms of species diversity, is predominantly non-native annual herbs. These species occur primarily in the more disturbed areas such as Filled sites. These Filled areas became areas of high disturbance as a result of the filling process and potential inclusion of a weedy plant species seed bank in the fill soil. The disturbance of the soil resulted in a potential release of plant nutrients and changed the water-holding capacity of the soil. The weedy annual species are adapted to those types of habitat conditions. Because of the large number of annual non-native "weedy" plant species established in the California flora, these disturbed areas generally become quickly dominated by these species. In contrast, the less disturbed areas support dominant native plant species such as saltgrass (*Distichlis spicata*), which continue to dominate many of the Grassland areas. Many of the areas referred to as Open habitats are former cattail-dominated wetlands that were drained, and the vegetation thatch remains, covering the ground. The thick thatch layer has remained over an extended period of time because of the lack of moisture for decomposition as a result of the drought conditions through 1993. These areas show the greatest change as the cattail thatch decomposes.

There is a general gradient of selenium concentrations in the surface soil of Open>Grassland>Filled (Ohlendorf and Santolo, 1994).

2.2.2 Aquatic Habitats

Although the goal of remediation at Kesterson Reservoir in the late 1980s was to dry the Reservoir and remove aquatic habitats, pools form at widespread locations in the former Reservoir in response to the winter rainy season. In many years the pools are extremely ephemeral and never achieve significant aquatic invertebrate populations. However, in some years, with higher rainfall or a more extended rainy period, pools persist for several months. Those longest-lasting pools with developed invertebrate populations offer the possibility of exposure from redissolved and bioaccumulated selenium to the Kesterson wildlife community. Waterfowl and shorebirds are of particular concern for exposure from the pools, because they are nesting at the time of pool occurrence in the late winter and early spring.

The ephemeral pools typically form in December or January and, in wet years, they may last until March or April. They vary from a few inches to 2 or 3 feet in depth and a few hundred square feet to several acres in area. Size, depth, and longevity of the pools are determined by

rainfall distribution and regional hydrology. When they occur, pools tend to form in the same locations each year.

2.3 Chemicals of Potential Ecological Concern

Studies at Kesterson Reservoir have included analyses of water and biota for a number of organic and inorganic constituents that could potentially be found in agricultural drainage (Saiki, 1986; Ohlendorf, et al., 1986, 1993; Hothem and Ohlendorf, 1989; Ohlendorf, 1989). Although some other chemicals (such as boron) occur at elevated levels at Kesterson, studies at Kesterson, other field sites, and in the laboratory indicate that selenium is responsible for the adverse effects observed in aquatic birds at the site. Therefore, selenium has been the focus of the ongoing monitoring program (as described above), and is the only COPEC to be considered in this EcoRA.

2.4 Assessment Endpoints and Measures

The identification of assessment endpoints is critical to problem formulation because these endpoints structure the assessment to address management concerns and are central to conceptual model development (USEPA, 1998). Assessment endpoints provide a transition between the ecological management goals for the site and measures used to evaluate the endpoints. Ecological goals for Kesterson include the following:

- Soil, surface water quality, and food source conditions capable of supporting small mammal populations that would be typical of similar habitats in the region
- Soil, surface water quality, and food source conditions capable of supporting migratory birds without measurable adverse effects on reproduction

2.4.1 Assessment Endpoints

Assessment endpoints are explicit expressions of the environmental values that are to be protected; they are operationally defined by an ecological entity and its attributes (USEPA, 1998). The relevance of the assessment endpoints is determined by how well they target susceptible ecological entities and whether they adequately represent management goals. The following three criteria were used in selection of assessment endpoints:

- Ecological relevance — Small mammals and migratory birds are integral components of the terrestrial ecosystem of the site, and aquatic species are known to use the ephemeral rainwater pools when pools are present.
- Susceptibility to the stressor — Research has shown that mammals and birds may be adversely affected by exposure to selenium.
- Relevance to management goals — Small mammals and migratory birds are valued ecological resources for the site and their protection represents management goals, as identified above.

The following assessment endpoints were selected for the EcoRA:

- Migratory birds – Survival and reproduction of terrestrial and aquatic birds without measurable adverse effects
- Small mammals – Survival and reproduction conducive to the maintenance of viable (self-sustaining) populations characteristic of grassland habitats in the region

2.4.2 Measures

Measures (sometimes referred to as "measurement endpoints") are the characteristics that are evaluated to provide an indication of whether adverse effects on assessment endpoints have occurred or are likely to occur. Two categories of measures that are predictive of the assessment endpoints were used for this assessment: (1) Measures of exposure were used to evaluate how selenium exposures could be occurring, and (2) Measures of ecological effects were used to evaluate the response of the assessment endpoints when exposed to selenium.

Measures of exposure include measured or modeled (estimated) concentrations of selenium in soil, surface water, and food-chain organisms, as well as receptor species. Measures of effects include food-chain bioaccumulation and the responses of small mammals and birds to dietary exposure of selenium. Measures of exposure and effects, as well as risk estimation modeling used in the Kesterson Reservoir EcoRA, are shown in Table 2-1.

2.5 Ecological Conceptual Site Model

The conceptual site model combines information on selenium, potential ecological receptors, potential exposure pathways, assessment endpoints, and measures of exposure and ecological effects. The model provides an overall picture of site-related exposures that can be used to focus the evaluation of selenium in the EcoRA. The development of the conceptual site model is presented in this section.

TABLE 2-1
Measures of Exposure and Effects and Associated Risk Estimation Used in the Kesterson EcoRA Model

Model	Exposure	Effects	Risk Estimation
Terrestrial	Selenium concentrations in soil, pore water, and the terrestrial food chain	Literature toxicity values for concentrations of concern for selenium in the diet Monitoring for teratogenic effects	Model estimates of the probability of exposure of wildlife to harmful levels of selenium
Aquatic	Selenium concentrations in water and aquatic invertebrates	Literature toxicity values for concentrations of concern for selenium in the diet Monitoring for teratogenic effects to semi-aquatic birds	Model estimates of the frequency of occurrence of dietary concentrations and potentially exposed eggs of receptor bird species

2.5.1 Physical/Chemical Parameters

The physical/chemical parameters used in the EcoRA models were:

- Soil selenium concentrations
- Soil pore-water selenium concentrations
- Pool water selenium concentrations
- Estimates of the extent of surface water ponding for various months

Data sources and synthesis of these parameters are discussed in Sections 1.1.3.1 and 2.6.1.

2.5.2 Identification of Representative Species

This section describes the criteria used to select representative species for Kesterson. Representative ecological receptors were identified as the terrestrial, aquatic, and semi-aquatic wildlife that are most likely to be affected by selenium. Representative receptors include primary and secondary consumers that are terrestrial (such as plants, soil invertebrates, upland birds, and mammals), aquatic (such as macroinvertebrates), and semi-aquatic (such as shorebirds and other birds that feed on aquatic biota). The potential plant and wildlife species that could represent ecological receptors were determined through meetings with the U.S. Fish and Wildlife Service (USFWS) and through direct observations of plants and wildlife. Representative species selected are from communities that are commonly found in the different habitat types at the site. The communities potentially exposed directly or indirectly (through the food chain) to selenium at Kesterson Reservoir are composed of terrestrial and free-swimming or benthic aquatic invertebrates, semi-aquatic and upland birds, and mammals. Although bullfrogs (*Rana catesbeiana*) are commonly found in the San Luis Drain, amphibians and reptiles have not been found to be associated with Kesterson ephemeral pools. There also are few data for evaluating exposures to those animals.

Representative ecological receptors were selected from these communities to fulfill as many of the following criteria as possible:

- Species that are known to occur or are likely to occur at the site
- Species that relate to the assessment endpoints selected
- Species that are likely to be maximally exposed to selenium
- Sedentary species or species with a small home range
- Species with high reproductive rates
- Species that are known to play an integral role in the ecological community structure at the site
- Species that are known or likely to be especially sensitive to selenium
- Species that are susceptible to bioaccumulation of selenium from a limited number of food items

- Species that are representative of the foraging guild or serve as food items for higher trophic levels

The representative species selected for the Kesterson Reservoir EcoRA are

- Terrestrial/upland representative species
  - Plants — terrestrial grasses and forbs
  - Invertebrates — insects and spiders
  - Birds (upland) — American kestrel, barn owl, and loggerhead shrike
  - Mammals — deer mouse
- Aquatic and semi-aquatic representative species
  - Invertebrates — free-swimming and benthic insects and micro-crustaceans
  - Birds (semi-aquatic) — killdeer, black-necked stilt, and mallard

Plants were selected because of their importance as habitat or forage for primary consumers. Invertebrates were selected because of their importance as prey species for secondary consumers. Representative vertebrate species (birds and mammals) were selected based on their occurrence or potential occurrence onsite. Bird species selected were further restricted to those species known to feed onsite. The primary criteria used to select vertebrate species include special-status listing, size of home range, representativeness of trophic level or feeding guild, and potential exposure to selenium.

2.5.2.1 Terrestrial Plants

Terrestrial plants are in direct contact with potentially contaminated soils and surface waters. They are non-mobile and would have high exposure to selenium. Plants may also bioaccumulate selenium in the leaves and other above-ground structures. They serve as a food source for terrestrial birds and mammals. Saltgrass (*Distichlis* sp.), prickly lettuce (*Lactuca* sp.), bassia (*Bassia* sp.), alkali weed (*Cressa* sp.), and other plant species were collected as part of the Kesterson Reservoir Biological Monitoring Program (KRBMP).

2.5.2.2 Terrestrial Invertebrates

Terrestrial invertebrates, such as insects and spiders, would be in direct contact with potentially contaminated soils or may consume contaminated prey, and, as such, they would be exposed to selenium. They have a relatively small range, have high reproductive rates, and serve an integral role in the upland ecosystem. They serve as primary prey items for some upland birds and small mammals. Spiders, beetles, grasshoppers, and other insects were collected as part of the KRBMP.

2.5.2.3 Upland Birds

Upland birds including hawks, falcons, owls, and songbirds are found year-round at Kesterson and may be exposed to selenium through ingestion of contaminated food items. American kestrels (*Falco sparverius*), barn owls (*Tyto alba*), and loggerhead shrikes (*Lanius ludovicianus*) were chosen as representative species for upland birds because of their high exposure potential and the extensive data base for these species (i.e., data on diet composition, foraging range, blood and egg selenium concentrations from Kesterson). Typically selenium in eggs sampled from seed-eating birds (such as mourning doves; *Zenaida macroura*) have been near background levels and these birds are not found at Kesterson year-round.

2.5.2.4 Mammals

Deer mouse (*Peromyscus maniculatus*) and coyote (*Canis latrans*) are fairly common and may be exposed to selenium through ingestion of food items. Western harvest mouse (*Reithrodontomys megalotis*), deer mouse, and California vole (*Microtus californicus*) were trapped as part of KRBMP, primarily to evaluate exposure of their consumers. Ornate shrews (*Sorex ornatus*) sometimes also are captured, but are not common on Kesterson (which is also typical of nearby reference sites).

2.5.2.5 Aquatic Invertebrates

Benthic and free-swimming macroinvertebrates and micro-crustaceans are primary consumers that fulfill many of the selection criteria. They would be in direct contact with potentially contaminated sediments and surface water, and, as such, they would be exposed to selenium. They have a small range, have high reproductive rates, and serve an integral role in the aquatic and semi-aquatic ecosystem. They serve as primary prey items for the semi-aquatic bird species chosen for the EcoRA (such as stilt, killdeer, or mallard). Various species of aquatic insects (such as midge larvae, water boatmen, or beetles) and micro-crustaceans (ostracods or cladocerans) have been collected from ephemeral pools at Kesterson Reservoir during most years since 1990.

2.5.2.6 Semi-Aquatic Birds

Semi-aquatic birds feed primarily on species associated with aquatic habitats and fulfill most of the selection criteria above. Black-necked stilts (*Himantopus mexicanus*), killdeer (*Charadrius vociferus*), and mallards (*Anas platyrhynchos*) were chosen as the receptors to assess the effects of selenium exposure through ephemeral aquatic habitats at Kesterson. Their habit of feeding in shallow waters for crustaceans and insects gives them a high potential for exposure to selenium through the ephemeral pool pathway. In addition, killdeer consume some terrestrial insects, and mallards consume some terrestrial plants. Eggs of all three species have been sampled at Kesterson Reservoir as part of the KRBMP.

2.5.3 Exposure Pathway Inclusion/Exclusion

The exposure pathway inclusion/exclusion evaluation is based on information gathered from the problem formulation and the selection of representative species, the probable completeness of each exposure pathway, and the potential for that pathway to be a major or minor route of exposure and risk.

A complete exposure pathway must exist for an exposure to occur. In addition to the presence of suitable habitat for ecological receptors, a complete exposure pathway must have the following elements:

- Contaminant source (such as selenium in soils and water)
- Mechanism for contaminant release and transport (such as solubility into porewater)
- Exposure point (such as soil or ephemeral pool)
- Feasible route of exposure (such as ingestion)
- Receptor (such as bird or mammal)

Contaminant sources and release mechanisms at Kesterson Reservoir consist primarily of on-site source areas (soil selenium inventory) and availability for plant uptake or the movement

of solubilized selenium through the soil profile into ephemeral pools. Ecological receptors can be exposed to chemicals in soil, sediment, or surface water via direct or secondary exposure pathways. Direct exposure pathways include ingestion, root uptake, and dermal contact. Secondary exposure pathways are limited to food-chain transfer of bioaccumulated selenium. Potential exposure pathways for representative species are summarized below, along with the rationale for inclusion/exclusion in the quantitative and qualitative evaluations conducted in the EcoRA.

Plants can absorb selenium via root uptake from sediment/soil or surface water. Selenium bioaccumulated within plant tissues (such as in the leaves) may result in the food chain transfer of selenium to higher trophic levels.

Terrestrial and aquatic invertebrates can absorb selenium through their epidermis and can accidentally or purposefully ingest sediment during feeding or burrowing. Benthic organisms are especially prone to exposure to selenium present in sediments, because some of them consume the organic materials from within the sediment (for example, midge larvae). Aquatic invertebrates serve as a major route of food-chain transfer, because they are prey for semi-aquatic birds (waterfowl, shorebirds).

Terrestrial and semi-aquatic birds and terrestrial mammals can be exposed to selenium in sediment/soil or surface water from several different behaviors. Animals can inadvertently or purposefully ingest sediment/soil while grooming, burrowing, or consuming contaminated prey species. Surface water can be ingested as a drinking water source or during bathing or grooming activities. Dermal contact with sediment/soil or surface water is considered to be a secondary route of exposure for birds and mammals. Dermal contact is of concern primarily with organic chemicals that are lipophilic (that is, have an affinity for fats) and can cross the epidermis of the exposed organism, but it is not considered an important exposure route for selenium.

Food-chain exposure may occur because selenium can be accumulated in plants that are consumed by herbivorous animals who are then eaten by omnivorous and insectivorous animals, carnivorous animals, and decomposers. Food-chain exposure is the primary exposure route of concern for birds and mammals.

Figure 2-1 shows a diagram of the conceptual site model.

2.6 Data Sources and Synthesis

2.6.1 Physical/Chemical Parameters

2.6.1.1 Data Sources and Synthesis: Pool Formation Parameters

This section describes the database and procedures used to estimate probabilities of ephemeral pool formation and areal extent of pool coverage at Kesterson Reservoir. The estimates to be obtained through analysis of weather data are: (1) the probabilities for ephemeral pool occurrence during individual months, and (2) estimates of the fraction of the Reservoir that will be ponded. These estimates are based on four basic assumptions:

- Monthly rainfall data from the nearby city of Los Banos can supplement the smaller rainfall record at Kesterson Reservoir.

- A simple algorithm for predicting pool initiation and duration within a given wet season yields adequate results.
- The algorithm for predicting ponding can also be extended to estimate areal coverage by ephemeral pools.
- The 127-year historical rainfall record (Los Banos and Kesterson data) will be representative of future rainfall distributions.

Based on these assumptions, estimated probabilities of pooling and of ponded area are given in Section 3.1.1.2.

Weather Database

Rainfall records at Kesterson Reservoir date from 1982, with detailed records available only since 1985. Data come from a USBR and a California Irrigation Management Information System (CIMIS) weather station. The CIMIS network of computerized weather stations is operated by the California Department of Water Resources (in Sacramento). These weather stations provide data on rainfall and they provide weather-based estimates of evapotranspiration from a standard vegetated surface (irrigated grass), which is denoted ET_o (Snyder, et al., 1994). The CIMIS weather station at Kesterson Reservoir was installed in 1989, and has provided nearly continuous meteorological data. In addition, USBR field staff collected pan evaporation rate data at Kesterson Reservoir from 1982 through 1987, and rainfall data from 1982 to 1996. It should be noted that there are minor gaps in the CIMIS rainfall data from Kesterson, and that these have been supplemented with USBR rain gauge data and CIMIS data from the nearby Los Banos station. Although this time interval includes drought years, as well as the extreme 1997-1998 El Niño year, a larger rainfall record is needed for purposes of estimating rainfall probabilities. Monthly rainfall data since 1874 are available for the Los Banos weather station from the California Department of Water Resources. Los Banos is located only 20 km (12 miles) away from Kesterson Reservoir, with very little topographic variation between the two locations. Nevertheless, the correlation between their rainfall records was examined before relying on the Los Banos data. Because of the short Kesterson record, this comparison can only be done for the years 1985 through 2000. The correlation plot shows that the Los Banos monthly rainfall data do provide a fair estimate of monthly rainfall at Kesterson Reservoir (Figure 2-2). The near-zero (2.4 mm) intercept, near-unit (0.998) slope, and high correlation ($r = 0.946$) indicate that the Los Banos monthly rainfall data can be used directly.

As a result, for purposes of this analysis, the 1874 through 1984 Los Banos monthly rainfall data were combined with the 1985 through 2000 Kesterson Reservoir rainfall data. Based on these data, Figure 2-3 shows the annual rainfall record. For comparison, it also shows the annual rainfall record from Fresno. The mean annual rainfall (water-year based, rather than calendar-year base) for the Los Banos-Kesterson area is 226 mm, with historical annual minimum and maximum values of 40 and 537 mm, respectively. Figure 2-4 shows the approximately log-normal frequency distribution of Los Banos-Kesterson annual rainfall from this data set. A tabulation of the 1874 through 2000 Los Banos and Kesterson monthly rainfall record is provided in Appendix B.

The fact that the available data set includes the 1997-1998 El Niño year substantially improves our chances of fairly estimating ponding probabilities, because that year yielded

the highest rainfall in the available 127-year record. Furthermore, most of the El Niño rainfall occurred within months when ephemeral pool environments have greatest potential for wildlife impacts (Figure 2-5).

Simplified Method for Predicting Ephemeral Pool Formation at Kesterson Reservoir

One of the two main inputs into our previously derived ponding model (Zawislanski, et al., 1997) is the CIMIS ET_o parameter. As noted previously, it is the estimated evaporation rate from a reference "crop" (irrigated grass surface), and depends on the local temperature, wind speed, and humidity. Inspection of 9 years of Kesterson Reservoir CIMIS data has shown that while daily ET_o records are quite variable from year to year, the cumulative ET_o record is not. This was shown for a smaller data set in our previous report, and is further illustrated in Figure 2-6, which shows that average ET_o values for Kesterson Reservoir can be used instead of actual daily ET_o values, without much loss of accuracy throughout most of the wet season. However, late in any particular season, cumulative ET_o values can diverge significantly from average cumulative ET_o values because of higher ET and accumulation of differences. We use the average of 1989 through 1998 cumulative ET_o values in later estimates of ponding probabilities. It should be noted that the CIMIS weather station at Kesterson Reservoir no longer reports ET_o because of inadequate station maintenance. However, the observed stability of the previous 9-year record indicates that use of the 1989-1998 average cumulative ET_o is suitable for predictions. The more traditional indicator of potential evaporation, pan evaporation, was measured at Kesterson Reservoir by USBR staff for several years prior to 1989 (primarily during years of active use for agricultural drainage water disposal). For Kesterson Reservoir, cumulative ET_o amounts to 71 percent of cumulative pan evaporation (Figure 2-7).

We now consider the simplification that soil water storage has a minor influence on rainfall ponding at Kesterson Reservoir. This simplification is based on two factors previously mentioned (Section 2.1.1). The first is the recognition that the water table is close to the soil surface during the wet season, even during drought years. This factor, combined with the partially saturated soil profile, leaves limited air-filled porosity for storage. In addition, the moderately low permeability of soils at sites most susceptible to rainfall ponding lessens the extent to which infiltration and drainage influences ponding. Thus, for purposes of estimating the inception and duration of wet season ponding, it appears reasonable as an approximation to overlook hydraulic interactions with the soil profile.

With these two simplifications (use of the average ET_o, and neglecting soil-water exchanges), only information on the temporal variation of rainfall within a given season is needed to estimate timing of ephemeral pool formation and duration. In the approximation that only rainfall and evaporation control ponding, pools will form at any time when the cumulative rainfall exceeds cumulative evaporation. As an initial approximation, the raw, average cumulative ET_o values were used. However, model calculations were found to under-predict ponding periods. Scaling down the average cumulative ET_o by a constant factor of 0.89 yielded optimized agreement between field-observed and predicted ponding. The optimization criterion selected was that of maximizing the number of correctly predicted days, minus the incorrectly predicted days. This optimization approach yielded a ratio of modeled versus observed ponding days of 0.965, with 86 percent of the observed ponding days correctly predicted. The result is graphically illustrated for two wet seasons, 1997-98

and 1998-99. Figure 2-8 shows plots of the 1997-98, and 1998-99 cumulative precipitation and 0.89 x (average ET_o).

In the two wet seasons evaluated in Figure 2-8, actual ponding was observed from days 72 (±1 day) through 222 (±10 days) in 1997-98, and was negligible in 1998-99 (November 1 is taken as Day 1 in these calculations). The simplified model predicted ponding during 1997-98 for days 73 to 211 (versus field-observed days 72 to 222), and no ponding for 1998-99. Comparison of the simplified approach to predicting ephemeral pool formation with field observations over the past 11 years is provided in Table 2-2. Good agreement is usually obtained between field observations of ponding and model predictions. Figure 2-9 graphically compares predictions versus observations of ponding for the subset of water years in which ponding is expected by the simple model (9 years out of the 11). The fact that a wide range of rainfall distributions and rainfall totals is included in these results gives support to the model's predictive ability, especially for non-drought years in which such information is most relevant. The success that this simplified model has had in predicting ephemeral pool formation and duration indicates that it could be useful in estimating future ponding at Kesterson Reservoir under a range of possible rainfall patterns.

TABLE 2-2
Comparisons between Observed Ephemeral Pool Onset-duration and Simplified Model Predictions for Water Years 1989-2000 at Kesterson Reservoir

	Beginning of Ponding (Day)		End of Ponding (Day)		Ponding Period (Days)	
Water Year	Observed	Predicted	Observed	Predicted	Observed	Predicted
1989-1990	108	108	118	115	11	8
1990-1991	118	None	150	None	33	0
1991-1992	102	104	169	162	68	59
1992-1993	72	67	168	181	97	115
1993-1994	108	99	129	137	22	44
1994-1995	75	65	176	181	102	117
1995-1996	93	92	165	154	73	61
1996-1997	38	39	150	164	113	129
1997-1998	72	73	222 ±10	211	149	139
1998-1999	*	None	*	None	0	0
1999-2000	84	103	149	138	66	36

Note: Day No. 1 is November 1st of a given water year.
* Denotes ponding restricted primarily to sites in which water table rise is the expected water source.

The calculations up to this point have been based on daily rainfall and daily average ET_o data. However, the larger historical weather data only provide monthly rainfall data, so that reliability of calculations based on monthly values must be tested. Using the previously described algorithm, but with only the monthly incremental Kesterson Reservoir rainfall data, the ponding model was applied to the 1990-2000 wet seasons. As before, the start of each wet season was defined to begin on November 1. For example, the 1990 wet season

begins on November 1, 1989. The cumulative monthly rainfall (CMR) is calculated within a given season relative to November 1. The CMR is compared on a month-by-month basis to 0.89 times the cumulative monthly average ET_o (0.89 x CM ET_o), to determine which months have CMR in excess of 0.89 x CM ET_o. The whole data set is then evaluated to determine the number of years in which CMR begins to exceed 0.89 x CM ET_o on a given month. The number of months within each year (beginning November 1) in which CMR exceeds 0.89 x CM ET_o is also calculated. These results provide the basis for estimating probabilities of pond initiation by a given month, and probabilities of pond duration, respectively. A test of the reliability of the "CMR minus (0.89 x CM ET_o)" procedure was performed by comparing its predictions to available field observations (1990 to 2000). Figure 2-10 compares the duration of ponding. Note that in these results, model predictions are discretized with 1-month temporal resolution. This comparison with the limited available field ponding data shows that the CMR - (0.89 x CM ET_o) model provides fairly reliable estimates of ephemeral pool initiation and duration.

Estimating the Areal Extent of Ponding

Information limited to whether ephemeral pools occur at Kesterson Reservoir within a given month is not very useful without information on the areal extent of the pools. The potential for wildlife exposure and effects of 1 percent versus 50 percent areal ponding within Kesterson Reservoir is clearly very different. Estimating the areal extent of ephemeral pools at Kesterson Reservoir with a simple model is difficult for two reasons. First, there is a limited database on ephemeral pool areal coverage. Such information, obtained from USBR aerial photographs, is currently available only for 8 days (March 15, 1995; February 6 and March 8, 1996; February 5, 1997; February 24 and April 17, 1998; and January 29 and February 11, 1999). Most, if not all, of the data on areal ponding are included in USBR Semiannual and Annual Reports on Kesterson Reservoir (Revised Monitoring and Reporting Program Number 87-149). Second, even if a much larger database were available, it is unlikely that a simple model could be accurately calibrated to this information because of complex hydraulics of pool-soil-topography-groundwater interactions. However, estimates of ephemeral pool areal extent are needed as part of the risk assessment. In this section, we describe our attempt at predicting ponding extent.

Because CMR - (0.89 x CM ET_o) appears to provide a good estimate as to whether pools occur, this parameter was tested for predicting the areal extent of ponding at Kesterson Reservoir. Qualitatively, negative to slightly positive values of CMR - (0.89 x CM ET_o) should be associated with insignificant ponding, while larger positive values should correlate with greater areal ponding. The available ephemeral pool area data plotted against CMR - (0.89 x CM ET_o) show this rough correlation (Figure 2-11). A second order polynomial fit, $y = 1.4 + 0.135x + 0.00127x^2$, is shown with these data ($R^2 = 0.90$). The fitting was done with exclusion of the one data point indicative of low ponded area at high CMR - (0.89 x CM ET_o) in order to obtain more conservative predictions. By "conservative," we mean predictions weighted to greater ponded areas. The fit shown in Figure 2-11 was obtained by minimizing the root mean square deviation with respect to all data, except the single value mentioned above.

2.6.1.2 Chemical Parameters

Reservoir-wide data collected between 1989 and 1998 were used to define the statistical distribution of selenium concentrations by habitat and trisection. This data set had been

collected as part of the ongoing biological and soil monitoring program (Zawislanski, et al., 1999; CH2M HILL, 2000). Within each trisection, six sites of each habitat type were chosen for long-term monitoring of soils for a total of 54 sampling sites. Soil samples were collected in July or August by inserting a 2.54-cm-diameter push-tube sampler to a depth of 15 cm from six stations in each habitat type of each trisection, for a total of 18 stations per trisection. The samples were collected at each site within a radius of about 1 meter of the station's center. From 1989 through 1991, only the top 15 cm of soil were sampled. Beginning in 1992, samples were collected using a hydraulic drill rig at intervals of 0 to 15, 15 to 50, and 50 to 100 cm. Samples were collected annually, except in 1997.

Soil samples were homogenized at field-moist conditions by hand-chopping and were passed through a 4.75-mm sieve. A known mass (between 20 and 30 g) of the homogenized subsample was then placed into an open metal can and oven-dried at 105°C for 24 hours to determine gravimetric moisture content. For the first 3 years, X-ray fluorescence (XRF) analysis was used to measure the total selenium concentrations of the sample (Giauque, et al., 1977). Starting in 1992, hydride-generation atomic absorption spectroscopy (HGAAS) of an acid digest of dry soil was used instead (Zawislanski and Zavarin, 1996). This method has a much lower detection limit and can be used for both near-surface and sub-surface soils. For the water-soluble selenium determination, a subsample of the homogenized soil (20 to 25 g) was used to prepare a 1:5 soil:water extract. Water-extractable selenium was analyzed using HGAAS.

Statistical parameters were determined for each combination of habitat and trisection, for both total and soluble selenium, using Statview v.4.5 software. These parameters include arithmetic, geometric, and harmonic mean; median; standard deviation and error; skewness; and kurtosis. Year-to-year trends in total and soluble selenium were also considered via statistical analysis.

A transfer factor between soil selenium and ephemeral pool selenium was calculated based on a correlation between pool selenium concentrations during the 1999-2000 wet season and surface soil selenium concentrations obtained at the pool sites just prior to the beginning of that season (October 18, 1999). The soils were collected at the end of the dry season in order to obtain samples that are likely to have the highest soluble selenium fraction due to reoxidation throughout the late spring and summer months. Based on our current knowledge of selenium (see section 3.1.1.1), soils collected just prior to the 1999-2000 wet season may also have higher soluble selenium fractions than in other recent years since it follows a wet season with below-average rainfall.

Ephemeral pool water has been collected annually during the wet season. Although some ephemeral pool sampling began in 1987, regular sampling at selected monitoring sites started during the 1992 wet season. During years when ephemeral pool formation is significant, the USBR and Lawrence Berkeley National Laboratory (LBNL) staff sample pool waters several (2 to 4) times per month for analyses of selenium and other constituents. Within a given site, pool selenium concentrations typically follow a general seasonal trend. During the initial days of ponding, selenium concentrations are relatively high. Over the first 20 to 40 days of ponding, pool selenium concentrations decrease because of dilution with additional rainwater, and because of diffusive transport and reduction in surface sediments. During this interval, pool selenium concentrations often exhibit more than 10-fold decreases. At still longer times, gradual increases in pool selenium concentrations occur, primarily as a result of

evaporative concentration. This cycle is observed during years when ephemeral pools are persistent, without any evident systematic year-to-year trends. Given the very dynamic nature of pool selenium concentrations, it is desirable to identify concentrations that are characteristic of each site. For this purpose, a selenium concentration typical of pool waters at 30 to 80 days within each site was selected for estimating soil-pool water selenium transfer factors.

2.6.2 Ecological

2.6.2.1 Terrestrial Habitats

The terrestrial food chain model is based on laboratory (Yamamoto, et al., 1998; Santolo, et al., 1999) and field studies conducted at Kesterson; measured soil, plant, and invertebrate samples collected from 54 permanent sampling sites located throughout Kesterson; and bird, bird egg, and small mammal (such as rodent and shrew) samples collected annually from 1989 to 1994 and analyzed for total selenium. These samples were collected for biological monitoring of Kesterson. Samples from the permanent sampling sites were collected within 25 meters of the center of each sampling site, whereas bird, bird egg, and small mammal samples were collected throughout Kesterson. Bird selenium concentrations were determined for liver (most samples collected before 1994) or blood samples (most samples collected in 1994 and later). Entire contents of bird eggs were analyzed for selenium, and small mammals were either analyzed for whole-body or liver selenium. Liver and carcass were analyzed separately for small mammals collected from 1989 through 1991 (whole-body concentrations in 1994 and later years were calculated using those data); in 1992 and 1993, samples were analyzed as whole animals, and in 1994 only livers were analyzed (whole-body selenium was estimated from a regression equation based on 1989 through 1991 liver: carcass selenium concentrations [Ohlendorf and Santolo, 1994]). Samples were stored at -70° F (-59° C) until they were shipped to a commercial laboratory (Environmental Trace Substance Research Center, Columbia, Missouri from 1989 to 1991 or Laboratory and Environmental Testing, Columbia, Missouri after 1991) on dry ice for total selenium analysis. Blood samples were analyzed by California Animal Health and Food Safety (formerly California Veterinary Diagnostic Laboratory Service, University of California, Davis). Sample preparation consisted of lyophilization, followed by homogenization, and sequential acid digestions (nitric acid followed by hydrochloric acid). Total selenium concentrations were determined using HGAAS. For blood analysis only, hydride vapor generation inductively coupled argon plasma spectrometry was used (Tracy and Möller, 1990). Lyophilization data were used to calculate percent moisture in all samples. All selenium concentrations are expressed as mg/kg on a dry mass basis.

2.6.2.2 Aquatic Habitats

Conducting an EcoRA for Kesterson that incorporates aquatic habitats required the summary of KRBMP data on ephemeral pool and aquatic invertebrate tissue selenium concentrations. Data from 1990 through 1999 were summarized by individual pool and averaged by trisection. All data were used to develop the regression relationship between waterborne selenium and aquatic invertebrate tissue selenium. Terrestrial plant and terrestrial invertebrate components of the bird diet were taken from the distribution of tissue selenium results (geometric mean, standard deviation) for those dietary components from the KRBMP

data. The relationship between ephemeral pool waterborne selenium and bird dietary item selenium concentrations used as EcoRA model inputs is shown in Figure 2-12.

The high variability and positive Y intercept of the Figure 2-12 relationship (1 µg/L in pond water equals approximately 10 mg/kg in invertebrate tissue) persist if the database is re-examined to exclude selected taxa or years or by examining invertebrate concentrations sampled 2-3 weeks after water samples were collected (to look for lag effects). The high baseline invertebrate values and overall variability are probably due to the variability in pond surface sediment selenium and the dependence of pond chemistry on the underlying soils. The invertebrates are variably dependent on sediment-associated food sources.

In addition to the data on pool water and bird dietary item chemistry, waterfowl and shorebird daily use data from the KRBMP were summarized by trisection to use in the EcoRA model. Bird use data during the late winter and early spring were required to develop a regression relationship to predict bird use based on the extent of ponding by trisection (Section 2.7.3, below). Bird use records were chosen for their proximity in timing to the aerial photography estimates of the extent of ephemeral pools. A summary of the regression relationships of bird use data versus extent of ponding by trisection is presented in Section 3.1.2.2.

2.7 Modeling

2.7.1 Physical/Chemical Model

The physical/chemical databases and models used to predict water-extractable selenium, transfer factors to pool selenium concentrations, and the extent of ponding by month were presented in Sections 2.6.1 and are developed into model predictions in Section 3.1.1, below.

2.7.2 Terrestrial Food Chain Model

The terrestrial food chain model was based on a previously developed model (Ohlendorf and Santolo, 1994) for predicting selenium concentrations in food chain items from predicted water–extractable soil selenium over a 20-year period (1992 to 2011). The development of transfer and weighting factors was previously described by Ohlendorf and Santolo (1994). Data from onsite monitoring at Kesterson from 1989 to 1994 were used to develop selenium transfer factors through the food chain (Figure 2-13). Weighting factors were based on food habit and home range studies conducted at Kesterson whenever possible. Where site-specific data did not exist for Kesterson, data from other studies were used.

Although there is a general increase in plant selenium with increasing water-extractable soil selenium, the relation between these two matrices is highly variable (Ohlendorf and Santolo, 1994), and a regression equation based on paired soil – plant samples collected from 1989 to 1994 was used to model uptake to plants. A realistic range of selenium bioavailability in soil (based on previous field data; Wahl, et al., 1994) was used in the model to develop predictions of dietary and tissue concentrations in the model species (American kestrel). Transfer factors, based on available measured selenium concentrations from Kesterson biological monitoring studies, were used to simulate selenium accumulation through the food chain. Detailed food habit, home range (Santolo and Yamamoto, unpublished data), and selenium accumulation data for kestrels from dietary selenium concentrations to blood and

egg concentrations (Yamamoto, et al., 1998; Santolo, et al., 1999) were used to model selenium accumulation through the Kesterson food chain. These same transfer factors, along with species-specific diet data, were used to model selenium accumulation in other bird species (such as barn owl, loggerhead shrike, and killdeer in years with no significant ponding).

2.7.2.1 Regression Models

The concentration of water-extractable selenium in soils was highly variable for all years, ranging from 0.14 to 156 mg/kg among the 322 samples from the 54 monitoring stations from 1989 though 1994. However, the slope of the regression lines was highly significant for both total and water-extractable selenium in the soil ($P < 0.001$ for both; Fig. 2-14). The relation between plant and water-extractable soil selenium concentrations was described as:

$$\text{Log Plant Se} = 0.78 + 0.235\ (\text{Log water-extractable soil Se});\ r^2 = 0.31,\ n = 52$$

Paired samples were used to develop the relationship between mushroom and soil selenium concentrations. Mushroom selenium concentrations were estimated using the regression equation:

$$\text{Mushroom Se} = (10^{(3.131+0.291\ *\ (\text{Log water-extractable soil Se}))})$$

Previous studies using kestrels (Yamamoto, et al., 1998) fed seleno-L-methionine mixed in with a commercial meat-based diet described the relation between diet and blood selenium ($r^2 = 0.88$; $P < 0.001$) as:

$$\text{Kestrel blood Se} = (10^{(0.34015\ +\ 0.55186\ *\ (\text{Log kestrel diet}))})$$

This relation can be described better via the second - order equation ($r^2 = 0.90$; $P < 0.001$):

$$\text{Kestrel blood Se} = (10^{(0.297\ +\ 0.335\ *\ (\text{Log kestrel diet}))\ +\ (0.285\ *\ (\text{Log kestrel diet})2)})$$

2.7.2.2 Transfer Factors

Transfer factors were used for all steps that used weighting factors. Because selenium concentrations in carnivorous invertebrates were significantly higher than those in non-carnivores, terrestrial invertebrates were separated into categories of non-carnivorous insects (such as herbivorous beetles, crickets, and grasshoppers) and carnivorous invertebrates (such as ambush bugs, scarab beetles, and spiders). We assumed that most terrestrial insects were eating only plants. The transfer factor was based on 667 spatially paired and temporally paired plant and insect samples collected from 1989 to 1994.

$$\text{Terrestrial insect Se concentration} = (\text{Plant Se concentration} * 1.0) * 2.8$$

We assumed that carnivorous invertebrates were eating only insects. The transfer factor was based on 218 spatially paired and temporally paired spider and insect samples collected from 1989 to 1994.

$$\begin{gathered}\text{Carnivorous invertebrate Se concentration} = \\ (\text{Terrestrial insect Se concentration} * 1.0) * 1.5\end{gathered}$$

We assumed that small reptiles (lizards and small snakes) that are eaten by American kestrels were eating only arthropods and that there is a higher abundance of herbivorous

insects than carnivorous invertebrates in most years. Few lizards have been observed at Kesterson in recent years and they have not been caught in pitfall traps. Western kingsnakes, terrestrial garter snakes, and gopher snakes have been observed during monitoring at Kesterson and six gopher snakes were captured in 1989 and three in 1990. Using these snakes as surrogates for "small reptiles" is considered to adequately estimate exposures. A transfer factor was calculated based on these spatially paired and temporally paired gopher snake and insect samples collected from 1989 to 1994.

Small reptile Se concentration =
(Terrestrial insect Se concentration * 0.7 +
Carnivorous invertebrate Se concentration * 0.3) * 1.43

We assumed that predators at Kesterson did not discriminate between deer mice, western harvest mice, and house mice, and fed on them based on availability. Diets for mice were determined from stomach content analysis of 158 deer mice, 47 western harvest mice, and 84 house mice captured at Kesterson. The transfer factor was based on 390 spatially paired and temporally paired plant, invertebrate, and mouse samples collected from 1989 to 1994.

Mice (whole-body) =
(Plant Se concentration * 0.794 + Mushroom Se concentration * 0.004 +
Terrestrial insect Se concentration * 0.101 + Carnivorous invertebrate
Se concentration * 0.101) * 1.485

Diets for shrews were determined from stomach content analysis of nine ornate shrews captured at Kesterson. The transfer factor was based on 47 spatially paired and temporally paired invertebrate and shrew samples collected from 1989 to 1994.

Shrew Se concentration = (Terrestrial insect Se concentration * 0.687 + Carnivorous
invertebrate Se concentration * 0.363) * 2.534

Diets for voles were determined from stomach content analysis of 55 California voles captured at Kesterson. The transfer factor was based on 107 spatially paired and temporally paired plant, invertebrate, and vole samples collected from 1989 to 1994.

Vole Se concentration =
(Plant Se concentration * 0.984 +
Terrestrial insect Se concentration * 0.016) * 2.009

Diets for small birds were determined from stomach content analysis of nine western meadowlarks collected at Kesterson. The transfer factor was based on 22 spatially paired and temporally paired plant and invertebrate samples collected from 1989 to 1994.

Small bird Se concentration =
(Soil Se concentration * 0.03 + Plant Se concentration * 0.12 +
Terrestrial insect Se concentration * 0.58 + Carnivorous
invertebrate Se concentration * 0.33) * 0.840

2.7.2.3 Terrestrial Model Verification

Soil selenium concentrations from samples collected in 1995, 1996, and 1998 were used as model input for verification of the model developed in 1994. Concentrations of selenium in

plant, invertebrate, and vertebrate samples collected in 1995 and 1998, as well as blood- and egg-selenium concentrations collected at Kesterson from free-living American kestrels and other bird species in all 3 years, were used to verify the model. For this assessment, selenium concentrations measured in 1995 and 1998 were compared to predicted selenium concentrations.

2.7.3 Aquatic Habitat Model

The Kesterson aquatic habitats EcoRA model was used to predict exposure of semi-aquatic birds to selenium through the ephemeral pool environment. Terrestrial plants and invertebrates were added to the model for mallards and killdeer (respectively) because these birds do not feed exclusively in the aquatic environment. In contrast, black-necked stilt were assumed to feed exclusively in the ephemeral pools.

The high year-to-year, climate-driven variability of ponding determines all aspects of the exposure of wildlife at Kesterson to selenium available through the ephemeral pools. The model was structured to represent natural climatic variability as measured at Kesterson for a hypothetical 1,000 years of data (Monte Carlo simulation approach).

The aquatic habitat model depends on estimates of the areal extent of ephemeral pools. Total month-end ponding was predicted based on the ponding model described in Section 2.6.1, above. Ponding by trisection was related to total ponding as shown in the digital aerial photography record. Regression relationships were then developed that predicted ponding by trisection. The first step in the aquatic habitat model was to estimate the extent of ponding by trisection at the ends of January, February, and March, for any given year. A summary of the steps in the aquatic habitat model follows:

- Establish a random distribution of 1,000 data points for total ponding at Kesterson Reservoir based on the statistical distribution of estimated ponding. All subsequent predictions were calculated for those hypothetical 1,000 years of record.
- Predict ponding by trisection for the period at the ends of January, February, and March. (Using total ponding to trisection-specific ponding relationships).
- Predict bird use by trisection based on ponding (using bird use to ponding relationships).
- Predict ephemeral pool selenium concentrations by habitat type based on the transfer factors from soil water-extractable to pool water selenium, as described in Section 2.6.1. Create a database of 1,000 random selenium transfer factors based on the measured distribution of transfer factors. Then use the area of habitat types by trisection to create weighted-average pool selenium concentrations by trisection (1,000 each). Trisection 1 = 61.1 percent Filled, 8.8 percent Grassland, and 30.1 percent Open. Trisection 2 = 9.9 percent Filled, 35.1 percent Grassland, and 15 percent Open. Trisection 3 = 55 percent Filled, 44.8 percent Grassland, and 2 percent Open.
- Predict aquatic invertebrate concentrations by trisection (1,000 each) based on the modeled pool water selenium concentrations and the Kesterson-specific regression relationship between those variables. Black-necked stilts were assumed to feed exclusively on these aquatic invertebrates.

- Estimate the trisection-specific selenium concentrations of the killdeer and mallard diets by adding selected terrestrial dietary items to the aquatic invertebrate diet. Create a random distribution of 1,000 data points for terrestrial plants (mallard diet) and insects (killdeer diet) based on the statistical distribution for these items by trisection from the KRBMP. Create average combined diets based on the assumptions that killdeer diets were 25 percent pool and 75 percent terrestrial invertebrates and mallard diets were 75 percent pool invertebrates and 25 percent terrestrial plants.
- Predict average Kesterson-wide dietary concentrations of selenium based on diet weighted by bird use by trisection (1,000 average dietary concentrations per species).
- Predict potential nests and eggs per species by trisection based on predicted bird use and estimates of the average number of eggs per nest (four each for killdeer and black-necked stilt, eight for mallard).
- Predict the potential egg selenium concentrations based on Kesterson-specific data on environmental transfer factors estimated for dietary selenium to egg selenium for the three species.
- For killdeer and stilt only, predict the potential number of hens having at least one egg per nest affected as a result of dietary selenium exposure (relationship based on egg selenium concentrations; limited to data on shorebirds).

The basic approach of the aquatic habitat model was to predict average daily bird use and dietary exposure from estimates of the extent of ponding. The diet and egg concentrations of selenium can be directly related to literature values on the potential effects of selenium on birds. As described in the literature on black-necked stilts and extended in our model to include killdeer (see last bullet, above), it was possible to predict the number of shorebird hens potentially affected by egg loss over the modeled 1,000 years of climate record.

SECTION 3

Analysis

The analysis phase links the problem formulation (Section 2) with the risk characterization (Section 4) and consists of the technical evaluation of ecological and chemical data to determine the potential for ecological exposure and adverse effects. The ecological management goals, assessment endpoints, and measures, as well as the ecological CSM developed during problem formulation (Sections 2.4 and 2.5) focus the analysis, which consists of two components: (1) exposure characterization and (2) ecological effects characterization. These two components are used to evaluate the relationships between receptors, potential exposures, and potential effects. The results of these evaluations provide the information necessary to estimate potential risks to the representative species under conditions defined for the site.

3.1 Exposure Characterization

The exposure characterization is used to evaluate the relationship between receptors at the site and potential stressors (chemical, biological, or physical entities that may result in adverse effects to one or more receptors or groups of receptors). Exposure is defined as the co-occurrence of a receptor and a stressor in both space and time. For risk to be present, there must be exposure. Therefore, to estimate risk, the exposure experienced by receptors must be described.

3.1.1 Physical/Chemical Parameters

3.1.1.1 Soil Selenium Concentration

The following discussion provides a justification for the use of the historic soil selenium data set to predict future impacts. Three approaches, detailed below, were taken to justify this approach. The first used field data from Reservoir-wide synoptic sampling to assess the magnitude and trend of changes in selenium concentrations. The second used the same data set, in combination with rainfall data, to compare selenium solubility in years following either relatively wet or dry winters. In the third approach, data from more than a decade of field and laboratory investigations were used to build a model that helps quantify long-term selenium re-oxidation rates at the habitat scale as well as at intensively monitored field sites.

Reservoir-wide Synoptic Sampling Selenium Data

Total and soluble soil selenium concentrations from Reservoir-wide synoptic sampling are shown in Figures 3-1 through 3-6, with statistical differences highlighted. There are very few year-to-year changes in the Filled and Grassland habitats. However, in the Open habitat, which comprises only 13 percent of the Reservoir area, there are many year-to-year differences, though an overall trend is absent. Moreover, due to the large degree of spatial variability, discerning statistically meaningful interannual and long-term trends is difficult. As discussed earlier, the most likely change in selenium distribution is one of selenium

oxidation to species of higher solubility. Solubility largely determines selenium's bioavailability and ecological exposure.

Interannual Variability in Soil Selenium Concentrations

The data set was examined to determine if annual fluctuations in soil selenium concentration could be associated with variability in the previous year's precipitation. The effects of "dry" versus "wet" winters were considered, because selenium reduction and leaching during the winter counteract oxidation that takes place primarily during the warm, dry summer months. The concentration of soluble selenium found in soil samples collected in July or August of each year from 1989 to 1998 was compared. Using weather data obtained from the CIMIS weather station in Pond 5, a "wet" year was defined as a year in which cumulative precipitation exceeded cumulative evapotranspiration as of February 28. Because of large differences in selenium concentrations and physical soil conditions among sample sites, each site was considered separately and subsequently combined by the nine habitat-trisection combinations. Figures 3-7 and 3-8 show the results of this analysis. In Figure 3-7, the fraction of soluble selenium during "wet" and "dry" years is compared for all habitats and trisections. In all cases, soluble selenium is higher following a dry winter, although, in most cases, this difference is statistically insignificant. Of the nine cases, Grassland sites in Trisections 1 and 2 are exceptions, with the fraction of soluble selenium following dry winters nearly double the levels during wet years. The dry year data in the Trisection 2 Filled sites are skewed by one remarkably high outlying value; otherwise, the wet and dry year values are similar. The Grassland data from all six sites in Trisection 1 are shown in detail in Figure 3-8, with the vertical line crossing through zero separating dry and wet years. There is a clear difference in the average fraction of soluble selenium present on either side of the line, despite much scatter. The noise results from differences among sites and other factors not considered, such as rainfall timing, intensity, and preceding year conditions. Nevertheless, this analysis provides a means to measure the impact of climatic conditions on soluble selenium levels. Although the T1 and T2 subsets of the Grassland data show statistically significant differences between wet and dry year soluble-selenium levels, these differences are small relative to the much greater uncertainties in numerous other parameters used in the ecological risk modeling.

Long-Term Trends in Soil Selenium Concentrations

In an attempt to discern long-term trends in soil selenium concentrations, a simple mass balance model was developed to evaluate the combined influences of selenium re-oxidation and leaching on total and water-extractable selenium concentrations. The current approach is a simplification of earlier models described in Benson, et al. (1992), and Wahl and Benson (1996). The model uses an annual time-stepping procedure to solve the coupled equations, as shown below:

$$SeT(t+\Delta t) = Se(t) - L\cdot SeX(t)\cdot\Delta t$$

$$SeX(t+\Delta t) = SeX(t) + R\cdot(Se(t)-SeX(t))\cdot\Delta t - L\cdot SeX(t)\cdot\Delta t$$

where:

SeT	Mass of total Se (g)
SeX	Mass of water-extractable Se (g)

L	First order water-extractable Se leaching rate constant (yr^{-1})
R	First order oxidation rate constant (yr^{-1})
t	Time (yr)
Δt	Time increment (yr)

This set of coupled equations can be used to calculate time trends in water-soluble and total selenium for a range of leaching and re-oxidation rates. For example, Figures 3-9a and b illustrate the expected time trends in total and water-extractable selenium for a range of values for L and R that fall within the range of previously estimated values (Benson, et al., 1992; Wahl and Benson, 1996).

For comparison, the soil selenium data collected from the Grassland habitat from 1990 to 1998 are also plotted. Figures 3-9c and d illustrate these same trends for the Open habitat. This analysis illustrates several important issues. First, without additional information, there is not a unique relationship between the time trends in the total and water-soluble selenium for various combinations of re-oxidation and leaching rate constants. Second, the large degree of spatial variability in total selenium concentrations overwhelms our ability to discern time trends from these data alone. Finally, time trends in water-soluble selenium concentrations are consistent with a combination of low re-oxidation rates (approximately 0.02 yr^{-1}) and moderate leaching rates (0.1 to 0.3 yr^{-1}).

Therefore, to improve our ability to distinguish between the relative influences of re-oxidation and leaching, we (1) used chloride concentration to independently establish leaching rates (Long, et al., 1990); (2) tracked the ratio between extractable and total selenium concentrations rather than tracking them individually; and (3) relied on data collected from well-characterized test plots instead of from Reservoir-wide data sites. Using these approaches, a simple graphical technique was developed for simultaneously assessing leaching and oxidation rates.

This detailed analysis has been applied to two test plots: the San Luis Drain Sediment Test Plot in Pond 7 (Benson, et al., 1990), and the Volatilization Test Plot in Pond 2 (Zawislanski, et al., 1996). Both have well-characterized selenium distributions and temporal monitoring data for chloride and extractable and total selenium. Figures 3-10a through 3-10e illustrate the results of this analysis, as plots of the ratio of extractable to total selenium versus the ratio between the current and initial chloride concentration for the different test plots. The ratio of current to initial chloride concentration can be used to determine the leaching rate (vertical lines in graphs). The re-oxidation rate can be determined by the type-curve that lies closest to the data points. For example, in Figure 3-10a, the leaching rate for Test Plot 1 is about 0.15 yr^{-1}, and the re-oxidation rate falls between 0.02 and 0.03 yr^{-1}. The advantage of this approach is that by plotting the standard deviation for the data points, the likely range of both the re-oxidation and leaching rates can be determined readily.

Multiple runs of this model, using data from various locations in the Reservoir along with data from previous investigations (Tokunaga, et al., 1991; Zawislanski and Zavarin, 1996) and general studies on selenium oxidation rates (Dowdle and Oremland, 1998; Losi and Frankenberger, 1998), have all shown selenium oxidation rates in the range of 0 to 5 percent per year. Modeling recent changes in soluble selenium concentrations indicates even lower

rates under natural conditions (1 to 3 percent). Leaching rates appear to be highly site specific, depending on both soil texture and depth to the water table. Kesterson-wide monitoring data suggest that the average leaching rate is 10 to 30 percent of soluble selenium per year. Changes at this order of magnitude are not likely to significantly affect ecological risk modeling, because far greater uncertainties exist in the calculation of other parameters, such as rainfall distribution, pool formation, and soil-to-water and water-to-biota selenium transfer factors.

Statistical Distribution of Selenium Used for Risk Assessment Calculation

The analyses presented here indicate that year-to-year and long-term changes in soluble selenium concentrations may be neglected with respect to the EcoRA model. The entire data set of selenium concentrations was used, grouped over the nine years but split by habitat and trisection. Table 3-1 shows statistical parameters for all nine subsets for both total and soluble selenium. Differences in selenium concentrations are most pronounced among habitats, with the highest levels found in the Open habitat and lowest in the Filled habitat. Soil in Trisection 1 generally contains the highest selenium concentrations, except in the Filled habitat, where total selenium does not significantly differ among trisections.

Statistical parameters can be used to determine the type of distribution present. Most data sets are dominated by low values, which is seen in the skewness being generally greater than 1. In those cases, the distribution is log-normal. In a few cases, as highlighted in Table 3-1, skewness is close to 1 and the median and mean values are similar, suggesting an approximately normal distribution. In Figure 3-11, histograms for total and soluble selenium in the Open sites, Trisection 1, are shown, along with a summary of statistical parameters, and a curve that represents a hypothetical normal distribution for the given mean. The skewness in the total selenium data (= 3.15) is evident here and the distribution is clearly log-normal. In the case of soluble selenium, the distribution is less skewed (= 1.02), so it is close to normal. These distributions are representative of the larger data set. The statistical parameters were used as input to the ecological risk model.

3.1.1.2 Rainfall Distribution and Pool Formation

Application of the Pool Prediction Model to the 1874 to 2000 Monthly Rainfall Data Set to Obtain Estimated Probabilities of Ponding

Given the fair success of the CMR - (0.89 x CM ET_o) model for matching the available field observations of ephemeral pool formation and duration (Section 2.6.1), we estimated probabilities of pond initiation within a given month, and probabilities of pool duration. This was accomplished by evaluating the larger data set (1874 to 2000) using the aforementioned procedure, assuming that the 127-year record is representative of future rainfall distributions. Figure 3-12 shows the estimated probability of ponding and the estimated probability of pool duration. Based on the historical monthly data, no significant ponding is expected for 43 percent of the wet seasons. Ponding for durations of 1, 2, 3, 4, 5, and 6 months is expected in about 9 percent, 11 percent, 14 percent, 15 percent, 6 percent and 1 percent of the wet seasons, respectively. During years in which ephemeral pools form, they are expected to initially form by the end of November, December, January, February, and March with probabilities of about 27 percent, 32 percent, 33 percent, 7 percent and 1 percent, respectively (Figure 3-13).

TABLE 3-1
Statistical Properties of the Total and Soluble Selenium Distributions by Habitat and Trisection

Descriptive Statistics: Total Se (mg/kg)

	Open T1	Open T2	Open T3	Fill T1	Fill T2	Fill T3	Grass T1	Grass T2	Grass T3
Mean	29.51	12.81	13.90	1.88	2:34	1.45	9.84	2.54	3.50
Std. Dev.	40.59	9.25	9.32	2.61	2.90	2.03	5.41	4.38	6.19
Std. Error	5.74	1.26	1.29	0.37	0.40	0.28	0.74	0.60	0.86
Count	50	54	52	49	53	52	53	54	52
Minimum	1.5	1.3	2	0.4	0.127	0.171	2.5	0.208	0.27
Maximum	229.1	41.8	38	14.5	12.712	9.2	30.826	30.9	40.871
Variance	1647.88	85.62	86.83	6.79	8.39	4.11	29.28	19.20	38.27
Coef. Var.	1.38	0.72	0.67	1.38	1.24	1.40	0.55	1.73	1.77
Range	227.6	40.5	36.0	14.1	12.6	9.0	28.3	30.7	40.6
Geom. Mean	16.17	9.85	10.91	1.20	1.23	0.79	8.58	1.41	1.93
Harm. Mean	9.07	7.10	8.14	0.94	0.73	0.54	7.42	0.92	1.25
Skewness	3.15	1.33	0.94	3.23	2.02	2.34	1.59	5.26	4.71
Kurtosis	11.91	1.52	0.15	11.06	4.03	4.93	3.69	30.97	24.46
Median	17.25	10.50	12.00	0.78	0.90	0.60	8.60	1.40	1.90

Note: Skewness at or below 1 indicates close to normal distribution, provided mean and median are similar. All other distributions are log-normal.

Descriptive Statistics: Weater-soluble Se (mg/kg)

	Open T1	Open T2	Open T3	Fill T1	Fill T2	Fill T3	Grass T1	Grass T2	Grass T3
Mean	0.86	0.44	0.53	0.33	0.19	0.09	0.61	0.12	0.13
Std. Dev.	0.69	0.40	0.75	0.75	0.20	0.13	0.60	0.14	0.12
Std. Error	0.10	0.06	0.10	0.10	0.03	0.02	0.08	0.02	0.02
Count	50	54	54	52	54	53	53	54	52
Minimum	0.064	0.048	0.052	0.01	0.006	0.002	0.103	0.01	0.021
Maximum	2.703	1.532	4.925	4.286	0.746	0.497	2.975	0.754	0.685
Variance	0.48	0.16	0.56	0.56	0.04	0.02	0.36	0.02	0.02
Coef. Var.	0.81	0.91	1.40	2.28	1.05	1.50	0.99	1.17	0.97
Range	2.6	1.5	4.9	4.3	0.7	0.5	2.9	0.7	0.7
Geom. Mean	0.59	0.31	0.34	0.11	0.09	0.04	0.42	0.07	0.09
Harm. Mean	0.38	0.22	0.25	0.06	0.04	0.02	0.30	0.05	0.07
Skewness	1.02	1.48	4.17	4.02	1.20	2.02	2.12	2.88	2.59
Kurtosis	0.23	1.05	20.60	16.23	0.31	2.80	4.82	9.46	8.00
Median	0.59	0.31	0.32	0.10	0.12	0.04	0.40	0.06	0.10

Note: Skewness at or below 1 indicates close to normal distribution, provided mean and median are similar. All other distributions are log-normal.

Estimated Ponding Probabilities Relative to January 31

Since wildlife use and nesting associated with ephemeral pools occurs during the later months of the wet season, we estimated probabilities of ephemeral pool occurrence during this period. For this purpose, the CMR - (0.89 x CM ET_o) model was applied to the 1874 to 2000 monthly database and examined for expected ponding from February to May. These results are shown with and without (predicted) ponding prior to January 31, and for ponding on January 31 through February 28, January 31 through March 31, January 31 through April 30, and January 31 through May 31 (Figure 3-14). The data were normalized to the number of years in the database (127), and expressed in terms of a frequency distribution in this figure. These results show that if February ponding occurs (based on calculations for January 31), it usually occurs in association with ponding in the immediately preceding months. Approximately 60 percent of the time ponding occurs in February, although previous month(s) within the wet season have also experienced ponding. These results also show that the expected frequency of ponding through the months of April and May is very low. Based on the historical rainfall record and the CMR - (0.89 x CM ET_o) model, only 7 out of the past 127 years would have resulted in ephemeral pools persisting through the end of April. One of these years was 1998, which is consistent with field observations. The model also correctly predicts that no ponding persists through the end of June.

Estimating the Probable Areal Extent of Ponding

Ephemeral pool areal coverage estimates were obtained for periods during the wet season critical to wildlife impacts. Given the monthly time intervals of the database, predictions were made for the end of the months of January, February, March, April, and May. The 127-year record of monthly CMR - (0.89 x CM ET_o) was combined with the second-order polynomial correlation described previously to obtain estimated percent ponding by month. Figure 3-15 shows histograms of the estimated probability for ponding areas (as percent of total Kesterson Reservoir area) at the end of each month. Figure 3-16 presents results from the same calculations, expressed as the estimated probability of exceeding specific ponded area values. This result indicates that areally and temporally extensive ephemeral pool coverage of Kesterson Reservoir is rare. For example, the estimated probabilities of greater than 10 percent areal coverage at the end of February, March, and April are about 25 percent, 16 percent, and 2 percent, respectively, based on historical rainfall data.

Pool area by trisection was estimated using aerial photographic records of pool coverage by trisection, as compared to total pool area, as expressed in the following relationships:

T1 Pools = (total Kesterson pool area [sq. ft.] * 0.304) + 194,034

T2 Pools = (total Kesterson pool area [sq. ft.] * 0.463) – 17,008

T3 Pools = (total Kesterson pool area [sq. ft.] * 0.233) – 177,020

Pool Selenium Concentration and Transfer Factors

As discussed earlier, ephemeral pool concentrations typically start at relatively high values, decrease during the main ponding period, and then increase to varying degrees toward the later stages of ponding. Figure 3-17, which plots data from site 3NW (collected from 1992 to 1998), is an example of this trend. Selenium in ephemeral pools occurs primarily as Se(VI), with up to about 30 percent as Se(IV). Decreases in pool selenium concentrations during

initial stages of ponding result from transport of selenium into shallow sediments, as well as from dilution by additional rainfall in some cases, and a relatively smaller loss due to volatilization. Year-to-year comparisons in selenium concentrations within individual pools reveal no obvious trends, and over the years the concentrations in individual pools have remained in a consistent range (Zawislanski, et al., 1997). This also applies to the "stable" concentration range shown in Figure 3-17. This concentration is ecologically more important than the initial high selenium spike, because (a) it is much longer in duration, and (b) it is closer to the spring-time period coincident with nesting. In addition, there is typically a lag of 30 or more days between pool formation and development of invertebrate communities that could provide food for semi-aquatic birds. The average "stable" concentrations for each pool were used in calculating a soil-to-pool transfer factor.

Figure 3-18 shows the relationship between typical ephemeral pool selenium levels and soluble selenium in soils underlying those pools. Although the relationship is not *a priori* linear, a linear fit is satisfactory ($r^2 = 0.791$). The transfer factor was derived from these data. A ratio of pool selenium to soluble soil selenium was calculated for each of the 10 sites and, subsequently, averaged at 0.024. This means that if the concentration of soluble selenium in the surface soils is 1,000 µg/kg (1 mg/kg), the corresponding concentration in the overlying ephemeral pool will be approximately 24 µg/L. Figure 3-18 shows the predicted values based on measured soluble soil selenium, which indicated that use of the transfer factor results in an approximation of the actual data. In some cases, this approximation slightly underestimates pool concentrations and, in a few cases, substantially overestimates those values. This is because the partitioning between soil and pool water depends on several variables, some of which are site-specific, including selenium fractionation in surface soils, ground cover, and the amount of decomposing litter, soil permeability, and depth to the water table. Therefore, it is impossible to derive a single transfer factor capable of precisely defining pool selenium levels. A polynomial relationship may better reproduce the actual pool selenium concentrations, but the linear approximation is accurate within a factor of 2 to 3, which is adequate, given the spatial and temporal variability in soil selenium concentrations.

3.1.2 Ecological

3.1.2.1 Terrestrial Habitats

The sample period during 1998 may be atypical because it represented an unusual year in terms of selenium exposure for much of the biota modeled (given the higher than normal rainfall). In 1998, selenium concentrations were higher in invertebrates than during most other years (CH2M HILL, 1999a). Also, some terrestrial birds may have had to forage more offsite during the breeding season, because much of Kesterson was flooded. Even so, model predictions (Section 2.7.2) for 1995 and 1998 agree relatively well with measured selenium in most biological media once they are weighted on the basis of ecological considerations (explained below) (Tables 3-2 and 3-3).

Foraging by American kestrels was determined to be 58 percent onsite based on a telemetry study of male kestrels conducted during the 1996 and 1997 breeding period at Kesterson (CH2M HILL, 1998). The percent of onsite foraging by other species was estimated from published foraging ranges and site-specific information (such as where they tended to nest). Because selenium is not evenly distributed throughout Kesterson and individual exposure

TABLE 3-2
Measured and Predicted Selenium Concentrations (mg/kg) in Various Biological Media, 1995[a]

	Measured			Predicted	
Media	*n*	Range	GM	$\bar{x}^b$ (SD)	$\bar{x}^c$ (SD)
Soil	49	0.006 – 2.5	0.19		0.05
Mushrooms				279	78.8
Plants	286	0.20 – 90	3.4	4.3 (1.3)	1.3* (0.6)
Insects	110	0.60 – 40	7.4	9.1 (2.7)	2.7* (1.3)
Carnivorous Invertebrates	35	4.5 – 48	18	13.4* (3.9)	4.0* (1.9)
Mice[c]	105	1.3 – 38	5.9	10.2* (3.1)	3.1* (1.5)
Deer mice[c]	36	1.3 – 38	6.3	9.8* (2.9)	2.7* (1.4)
Voles[c]	38	1.4 – 19	4.5	8.7* (2.6)	2.6* (1.3)
Shrews[c]				23.1	6.5
Small birds[d]				8.2	2.3
Kestrel blood[e]	5	2.3 – 7.9	3.4	5.7* (0.62)	1.8* (0.91)
Kestrel egg[e]				10.0	2.8
Barn owl blood[f]	21	1.9 – 9.8	4.9	9.9* (1.4)	3.0* (1.5)
Barn owl egg[f]				34.6	9.8
Shrike blood[g]				8.3	2.4
Shrike egg[g]				25.92	7.1
Killdeer blood[h]				8.2	2.3
Killdeer egg[h]	12	2.3 – 12.5	5.7	24.4* (4.4)	7.7 (3.6)

* – Predicted means followed by an asterisk are significantly different than the measured mean (Tukey-Kramer $P \leq 0.05$)

[a] – Based on 1995 measured water-extractable soil selenium

[b] – Calculated without taking into account relative areal extent of different habitats

[c] – Weighted by habitat type (13% Open, 31% Grassland, and 56% Filled)

[c] – Whole-body Se

[d] – Blood-Se

[e] – American kestrels were assumed to forage onsite 58%

[f] – Barn owls were assumed to forage onsite 75%

[g] – Loggerhead shrikes were assumed to forage onsite 85%

[h] – Killdeer were assumed to forage onsite 60%

TABLE 3-3
Measured and Predicted Selenium Concentrations (mg/kg) in Various Biological Media, 1998[a]

	Measured			Predicted	
Media	*n*	Range	GM	$\bar{x}^b$ (SD)	$\bar{x}^c$ (SD)
Soil	53	0.009 – 4.9	0.19		0.05
Mushrooms				278	78.1
Plants	240	0.20 – 68	3.8	4.3 (1.5)	1.2* (0.59)
Insects	104	1.8 – 61	12.8	9.2* (3.2)	2.5* (1.3)
Carnivorous Invertebrates	35	8.1 – 36	17.1	13.5* (4.8)	3.8* (1.9)
Mice[c]	79	0.3 – 28	4.7	10.3* (3.8)	2.9* (1.4)
Deer mice[c]	30	0.90 – 11.1	3.9	9.9* (3.6)	2.8* (1.4)
Voles[c]	7	0.3 – 8.7	2.7	8.9* (3.1)	2.5 (1.2)
Shrews[c]	1		3.8	23.1	6.5
Small birds[d]	15	7.4 – 64	15.7	8.6* (3.1)	2.4* (1.2)
Kestrel blood[e]	23	2.3 – 31	7.3	5.7 (0.74)	1.7* (0.89)
Kestrel egg[e]	5	2.3 – 5.1	3.4	10.5* (3.3)	2.9 (1.4)
Barn owl blood[f]	5	3.3 – 5.6	4.0	7.9* (1.3)	2.4* (1.2)
Barn owl egg[f]	3	6.0 – 7.0	6.6	23.7* (9.1)	6.5 (3.1)
Shrike blood[g]	9	9.8 – 38	14.5	8.4* (1.4)	2.5* (1.3)
Shrike egg[g]	4	4.5 – 6.0	5.3	27.1* (10.7)	7.4 (3.6)
Killdeer blood[h]	5	7.6 – 57.0	30.4	8.2* (0.73)	2.5* (1.3)
Killdeer egg[h]	41	1.9 – 31	8.0	24.7* (5.3)	7.2 (3.6)

* – Predicted means followed by an asterisk are significantly different than the measured mean (Tukey-Kramer $P \leq 0.05$)

[a] – Based on 1998 measured water-extractable soil selenium

[b] – Calculated without taking into account relative areal extent of different habitats

[c] – Weighted by habitat type (13% Open, 31% Grassland, and 56% Filled)

[c] – Whole-body Se

[d] – Blood-Se

[e] – American kestrels were assumed to forage onsite 58%

[f] – Barn owls were assumed to forage onsite 50%

[g] – Loggerhead shrikes were assumed to forage onsite 85%

[h] – Killdeer were assumed to forage onsite 60%

can vary because of various factors (such as an animal's roosting or nesting location, foraging range, or prey availability), a selenium range was devised by weighting selenium concentration using the percentage of coverage of the three habitat types. For the weighted

mean model, it was assumed that animals forage in the various habitats (that is, Grassland, Filled, and Open) in the same proportions that the habitats occur at Kesterson (31 percent Grassland, 56 percent Filled, and 13 percent Open). However, these habitats do not occur in the same proportion in each trisection, so an animal living in Trisection 3 would probably have less exposure to Open habitat areas (that is, the areas with the highest selenium levels) than an animal living in Trisections 1 or 2. This is reflected in the model by the difference between the predicted mean and weighted mean selenium concentration. The weighted mean for egg-selenium concentrations in most cases is less than, but similar to, the measured geometric mean (GM) selenium concentration, and selenium concentrations for the various biota are expected to fall between the overall and weighted mean concentrations.

For 1995 and 1998, the geometric mean of all measured selenium concentrations for birds and mammals ($n \geq 3$) generally fell between the predicted mean and weighted mean. In 1995, killdeer eggs were slightly lower than the predicted weighted mean (Table 3-2). In 1998, the modeled weighted means for small birds, kestrel blood (not significantly), shrike blood, and killdeer blood were under-predicted. However, it is noteworthy that the model adequately predicted egg selenium in all species, despite the fact that conditions were unusual that year. Small bird liver selenium concentrations were converted to blood selenium based on a regression equation developed from western meadowlark blood and liver concentrations ($r^2 = 0.78$, $n = 10$, $P = 0.001$). The database of small birds upon which the transfer factor and prediction were based is composed of estimated blood selenium (from livers) from 22 western meadowlarks and two sparrows collected in 1989 and 1990, and the small birds measured during 1998 included blood from six white-crowned sparrows and one western kingbird. Differences also may be partly a result of dietary and home range differences among the species modeled and measured.

Based on water-extractable soil selenium concentrations, predicted selenium concentrations provide a realistic range of selenium in biota. However, because the model assumes that animals use all of the habitats at Kesterson, it may not predict selenium concentrations accurately in species that use any one habitat type exclusively or that forage primarily offsite. Furthermore, this model is based on Kesterson-specific data, so it may not be applicable to other sites.

3.1.2.2 Aquatic Habitats

Bird Use

Bird use at Kesterson Reservoir is measured as part of the KRBMP. Daily use was estimated by trisection for days close to the time of aerial photographs. Trisection and species use estimates were compared to flooded area to develop regression relationships for use in the EcoRA aquatic exposure model. All species showed positive, linear relationships between daily use and the extent of ponding. Graphical relationships and regression equations are presented in Figures 3-19 to 3-21. The relationships were all derived from ponding and bird use in the January-through-March period and were used to predict bird use for those months in the model.

Pool and Aquatic Invertebrate Selenium Concentrations

Some exposure of wildlife to selenium from ephemeral pools occurs through direct exposure to waterborne selenium, but the primary means is through ingestion of aquatic

invertebrates. Table 3-4 shows the average concentrations of selenium in water and aquatic invertebrates from the 1990 through 1999 Kesterson Reservoir monitoring program.

TABLE 3-4
Geometric Mean Water and Dietary Selenium Concentrations, Kesterson Reservoir (Number of Samples in Parentheses)

Parameter	Trisection 1	Trisection 2	Trisection 3
Water, 1992-1999 (total selenium, µg/L)	8.4 (62)	6.6 (49)	7.4 (39)
Aquatic Invertebrates, 1992-1999 (whole body concentrations, mg/kg as dry weight)	27.4 (74)	17.4 (56)	14.9 (53)
Terrestrial Invertebrates, 1989-1998 (whole body concentrations, mg/kg as dry weight)	11.6 (400)	9.9 (409)	7.4 (365)
Terrestrial Plants, 1989-1998 (whole plant concentrations, mg/kg as dry weight)	4.4 (690)	3.4 (691)	3.3 (749)

Waterborne and aquatic invertebrate selenium concentrations are positively correlated for the Kesterson Reservoir ephemeral pools. Therefore, the following relationship (as shown in Figure 2-12) was used to predict invertebrate tissue concentrations based on predicted poolwater concentrations, where:

$$\text{Pool aquatic invertebrate selenium (mg/kg as DW)} = 10\text{\^{}}(\text{Log (Pool Water Se)}*0.393+0.986)$$

In addition to their diet of aquatic invertebrates when pools are present, killdeer were assumed to consume terrestrial invertebrates 75 percent of the time, while mallards were assumed to feed 25 percent of the time on terrestrial plants. Black-necked stilts were assumed to feed solely on aquatic invertebrates in the ephemeral pool environment and to leave Kesterson when pools were not present. Terrestrial components of the birds' diets were estimated based on the statistical distribution of selenium concentrations for plants and invertebrates as taken from the terrestrial model. Table 3-5 shows mean terrestrial component concentrations by trisection.

Waterborne selenium concentrations were predicted in the EcoRA model based on changing climatic regime and estimates of the month-end extent of ponding. The model uses the statistical distribution of transfer factors from water-extractable soil selenium to poolwater selenium to predict an array of possible poolwater selenium concentrations by trisection. Table 3-5 shows the predictive relationships expanded in the model to an array of 1,000 random, annual average conditions. The basic construction of the model was described in Section 2.7.3.

TABLE 3-5
Means and Standard Deviations of Data Expanded in the Monte Carlo Simulations of the Aquatic EcoRA Model

Parameter	Mean	Standard Deviation
Water-Extractable Selenium Concentration (µg/kg) to Poolwater Selenium Concentration (µg/L) Transfer Factor	0.0239	0.0188
Total Percent Ponded Area, Kesterson Reservoir	End of January = 6.3 End of February = 6.6 End of March = 3.4 End of April = 0.03	End of January = 13 End of February = 14 End of March = 8 End of April = 0.22
Terrestrial Plants, Selenium Concentration	T1 = 5.0 T2 = 4.0 T3 = 3.5	T1 = 10.0 T2 = 4.8 T3 = 8.1
Terrestrial Invertebrates, Selenium Concentration	T1 = 12.5 T2 = 9.4 T3 = 8.1	T1 = 8.9 T2 = 7.7 T3 = 6.8

3.2 Ecological Effects Characterization

The ecological effects characterization consists of an evaluation of available toxicity or other effects information that can be used to relate the exposure estimates to a level of adverse effects. Stressor-response (i.e., effects) data that may be used to evaluate ecological risks resulting from chemical exposures fall into three general categories: (1) literature-derived or site-specific single-chemical toxicity data, (2) site-specific ambient media toxicity tests, and (3) site-specific field surveys (Suter, et al., 2000). All three categories of data were available for the assessment of ecological risks at Kesterson Reservoir and are summarized below.

3.2.1 Terrestrial Habitats

Monitoring of terrestrial species (for example, CH2M HILL, 1999a, 1999b) and studies of small mammals (Clark, 1987; Clark, et al., 1989) and predatory birds (Santolo and Yamamoto, 1999) at Kesterson are among the few studies of selenium effects on free-living terrestrial wildlife (especially birds and small mammals) conducted to date. There also have been very few laboratory studies investigating the effects of selenium on terrestrial animals (eastern screech-owls [*Otus asio*; Wiemeyer and Hoffman, 1996], and American kestrels [Yamamoto, et al., 1998; Santolo, et al., 1999; Yamamoto and Santolo, 2000]). These studies provide most of the information on effects of selenium in terrestrial species, and no guidelines have been established specifically for terrestrial wildlife species. Because of the limited data on free-living terrestrial animals, evaluation of effects on terrestrial systems is primarily extrapolated from effects on aquatic and semi-aquatic species.

Although adverse effects of dietary selenium have been observed in both livestock (O'Toole, et al., 1996; Puls, 1988) and laboratory mammals (Halverson, et al., 1966; Schroeder and Mitchener, 1971), these effects have not been observed in free-living mammals at Kesterson (Clark, 1987; Clark, et al., 1989; Ohlendorf and Santolo, 1994). In 1984, Clark (1987) investigated selenium accumulation in mammals at Kesterson prior to cessation of drainwater deliveries. No adverse effects of selenium were found in mammals collected

from Kesterson Reservoir for this study or a subsequent study in 1986 during the time when selenium toxicosis was observed in birds (Clark, et al., 1989; Ohlendorf, 1989). However, Clark (1987) suggested that there could be future or long-term effects to mammals based on reproductive effects identified in birds.

In the study by Clark (1987), shrews and voles had the highest concentrations of selenium. If populations of small mammals at Kesterson were to be affected, those species probably would be most likely to show these effects. Small mammal populations at Kesterson are variable from year to year in terms of species abundance (CH2M HILL,1995). A small mammal trapping study conducted in 1999 at Kesterson and three sites in the vicinity of Kesterson (i.e., the adjacent Freitas Unit of the San Luis National Wildlife Refuge, Grasslands State Park, and the area of the Delta-Mendota Canal [DMC] from which soil was taken for filling Kesterson in 1988) showed differences in species densities among the sites (CH2M HILL, 1999b). Over a three-month period (i.e., July – September) in 1999 with more than 10,000 trap-nights, two shrews were captured at Kesterson and three shrews were captured at nearby Grasslands State Park. No shrews were captured at the San Luis National Wildlife Refuge or at the DMC site. Eleven voles were captured at Kesterson and at the San Luis Refuge site, whereas nine were trapped at the Grasslands State Park and only one at the DMC site.

Deer mice, western harvest mice, and house mice were found at all the sites (CH2M HILL, 1999b). The observed differences in the numbers of animals and trap success among the four sampling sites may have been due to various habitat factors including disturbance, available water, and differences in microhabitat. The dry conditions of the sites may especially affect shrews because they have high evaporative water loss through respiration and are unable to regulate water loss at low humidity. Because shrews require a source of free water as well as adequate vegetation cover to provide protection and aid in retaining moisture to survive (Chew, 1951; Churchfield 1990) it is not surprising that shrews are not common at Kesterson. Thus, there is no evidence from the recent small mammal study (CH2M HILL, 1999b) to indicate that small mammal populations (particularly shrews and voles) are adversely affected by selenium, and other environmental factors are more likely to account for any observed differences.

Reproductive effects of selenium reported in wild aquatic birds include embryo mortality and teratogenesis, and failure of adult birds to nest (Skorupa and Ohlendorf, 1991; Ohlendorf, et al., 1990). Such effects have been produced in laboratory dietary studies using both organic and inorganic forms of selenium (e.g., in mallards [Heinz, et al., 1987, 1989] and domestic chickens [*Gallus gallus*; Gruenwald, 1958; Ort and Latshaw, 1978]). Selenomethionine, the most bioavailable and toxic of the different selenium compounds studied, is associated with reduced reproductive effects in mallards at dietary concentrations as low as 7 – 8 mg/kg dry mass (Heinz, et al., 1989; Stanley, et al., 1996). Santolo et al. (1999) observed lower fertility in eggs from kestrels fed 12 mg/kg selenomethionine. In screech-owls fed selenomethionine at concentrations similar to the concentrations found in dietary items at Kesterson (about 12 mg/kg), effects on fertility were not measured, although other reproductive effects were reported (Wiemeyer and Hoffman 1996). Lack of reporting on fertility effects may be due in part to a general practice of simply including infertile eggs as inviable eggs in studies of selenium effects in birds (e.g., "infertility" effects may not be separated from "embryotoxic" effects in the overall measurement of hatchability). Failure to measure infertility as a separate endpoint may be

due to the difficulty often associated with distinguishing infertile eggs from those containing embryos that have died very early in development. Nevertheless, decreased fertility is a distinct effect from embryotoxicity, particularly in that it indicates a mechanism acting on adult, rather than embryonic, physiology. Results obtained in kestrels suggested that infertility may be a potentially important factor contributing to the overall reproductive impairment in some species. However, in mallards and night-herons fed 10 mg/kg as selenomethionine, egg fertility was not reduced compared with controls (Heinz, et al., 1987; Smith, et al., 1988). The continued occurrence of similar concentrations of selenium in plants, invertebrates, and small vertebrates at Kesterson suggests some potential for reproductive impairment in breeding birds that forage extensively in this area (Ohlendorf and Santolo, 1994).

Since 1988, when low areas of Kesterson were filled to create upland habitat, selenium-caused effects such as embryo deformities, reduced egg viability, or wildlife mortality have not been found, although elevated levels of selenium continue to occur in bird eggs and other wildlife. The selenium chemistry data indicate a low-level risk of avian reproductive effects; however, given the generally small numbers of breeding birds at Kesterson and the high rates of egg loss due to predation, low-level effects would be difficult to detect so it is not surprising that they have not been detected.

Previous efforts to monitor and assess selenium impacts to birds at Kesterson and other selenium-contaminated sites have focused primarily on potential effects on reproduction (Ohlendorf and Santolo, 1994). However, there are other risk factors associated with elevated selenium including loss of muscle mass, as observed by Ohlendorf, et al. (1988, 1990) at Kesterson. American coots (*Fulica americana*) exposed to high environmental levels of selenium had body masses that averaged 25 percent less than those collected from a reference site. Other studies have reported significant body mass loss in adult birds exposed to dietary levels of selenium of 20 to 30 mg/kg (Albers, et al., 1996; Smith, et al., 1988; Heinz and Fitzgerald, 1993a, 1993b; Wiemeyer and Hoffman, 1996). More recently, Yamamoto and Santolo (2000) found that American kestrels exposed to dietary levels of 12 mg/kg selenomethionine exhibited significantly lower lean mass than birds exposed to 6 mg/kg and below; this effect was observed over the 6-month study period, long after the depuration of selenium by kestrels (Yamamoto, et al., 1998). Similar effects were observed in quail fed 22 mg/kg selenomethionine over a 1-month period (Yamamoto and Santolo, unpublished data). This suggests that the body condition of kestrels, and perhaps other birds that use high-selenium areas, may be impaired at concentrations below or comparable to those known to directly affect reproduction.

While reduced body condition in wild birds may not have immediately lethal results, such alterations can nevertheless have important long-term consequences. For instance, in some bird species, winter body condition or fat storage is an indicator of whether breeding will be successful (Newton, 1979; Alisauskas and Ankney, 1985; Wiebe and Bortolotti, 1995). American kestrels subjected to moderate to significant reductions in body fat and lean mass during the pre-laying and laying periods produce smaller eggs with lower hatchability (Wiebe and Bortolotti, 1995, 1996), and females may delay egg formation until their condition improves (Meijer et al., 1989; Aparicio, 1998). Furthermore, Iko (1991) found that American kestrel parents in good physical condition were more likely to deliver more food to offspring than were parents in poor condition. Based on these observations, birds

exposed to elevated dietary selenium during the winter may not be in adequate condition for surviving migration to the breeding location and/or successful reproduction because of persistent reductions in muscle mass and body fat. Nevertheless, there is not sufficient information available to assess the significance of selenium-related weight loss under field conditions.

3.2.2 Aquatic Habitats

Impacts to waterfowl and shorebirds using Kesterson Reservoir can be estimated by comparing the selenium concentrations in dietary items to known toxic-effect levels. Recently established guidelines for trace element exposure indicate dietary concentrations of concern from 1 to 4 mg/kg selenium in diet (dry weight basis) and potential toxic effects when dietary concentrations exceed 4 mg/kg (USDI, 1998). Table 3-6 summarizes dietary and tissue effect levels that can be used to evaluate potential toxic effects of environmental selenium concentrations to mammals and birds. There are differences in potential dietary exposures and sensitivity among aquatic bird species that may use Kesterson Reservoir in wet years. Mallards are among the most sensitive species, black-necked stilts and killdeer are moderately sensitive, and American avocets (*Recurvirostra americana*) are less sensitive.

TABLE 3-6
Toxicity Guidelines for Selenium Exposure (from Beckon and Dunne, 2000; J. P. Skorupa, pers. comm.)

	Level of Effect		
Criteria	**None / Background**	**Level of Concern**	**Toxicity**
Water (μg/L, total recoverable Se)	less than 2	2 to 5	more than 5
Diet (mg/kg dw)	less than 3	3 to 7	more than 7
Waterbird eggs (mg/kg dw)	less than 6	6 to 10	more than 10

Notes:
Except for avian eggs, these guidelines are intended to be population-based. Thus, trends in means over time should be evaluated. Guidelines for avian eggs are based on individual level response thresholds (e.g., Heinz, 1996; Skorupa, 1998).

Measured and modeled egg concentrations may be compared to probable toxic effects levels, as well. Toxicity guidelines suggest that egg selenium concentrations exceeding 6 mg/kg may indicate potential reproductive impairment (Table 3-6).

SECTION 4

Risk Characterization

The risk characterization evaluates the evidence linking exposures to COPECs with their potential ecological effects among the representative species identified for the site. Based on the potential risks of adverse effects to those ecological receptors (and similarly exposed species), it leads to the conclusions (Section 5) and recommendations (Section 6). The risk characterization consists of three portions: (1) the risk estimation, (2) the risk description, and (3) the uncertainty analysis.

4.1 Risk Estimation

4.1.1 Quantitative Evaluation

4.1.1.1 Terrestrial Habitats

Table 4-1 presents the results of the model run using water-extractable soil selenium data from LBNL (using 1,000 Monte Carlo simulations for each habitat type [total run = 3000]). Selenium concentrations for the various media modeled are expected to fall between the overall and weighted mean selenium concentrations, depending on location or home range of the individual and other factors. For example, individuals that use Trisections 1 and 2 have a greater opportunity for higher exposure than individuals using Trisection 3, because the percentage of open habitat is higher in Transections 1 and 2.

Selenium concentrations in the diet and eggs of target species were predicted using "best judgment" of the percent of onsite foraging based on published and observed foraging ranges. Foraging ranges varied by species. A second, worst-case was also calculated assuming 100 percent onsite foraging for all target species. The model does not predict the lowest measured concentrations because onsite foraging was always assumed in the model, although some eggs sampled may have been from birds foraging 100 percent offsite. The "best judgment" case was the better predictor of average selenium concentrations found in target species, even in those years that had individual measured samples with very high egg selenium concentrations (see Tables 3-2 and 3–3).

Based on the predicted water-extractable soil selenium, selenium levels in terrestrial food chain items other than mushrooms and shrews will generally be low. Of the selected bird diets and eggs, only loggerhead shrike and killdeer egg selenium levels are predicted to be more than 6.0 mg/kg (dry weight) when weighted by habitat type. Overall, mean selenium concentrations indicate that individuals that forage in Open habitats to a greater degree than the 13 percent that this habitat occupies at Kesterson will exhibit higher selenium concentrations.

The availability of selenium through the terrestrial food chain fluctuates from year to year, but terrestrial animals foraging at Kesterson exhibit fairly stable selenium concentrations (for example, CH2M HILL, 1999a). Typically, the relatively large changes of available

selenium occur in small areas and may make up a relatively small percentage of the animal's foraging range. This is different than in the aquatic food chain, where animals may depend on ephemeral pools (that is, they may make up a large percentage or all of the animal's foraging area) and reflect the pool selenium concentration. Therefore, locally high soil or plant selenium levels will typically not be reflected in higher-trophic-level animals because they forage more widely. As long as conditions at Kesterson do not change greatly, there should be no significant change in selenium concentrations in higher-trophic-level terrestrial animals using the site.

TABLE 4–1
Arithmetic Means of Predicted Selenium Concentrations (mg/kg) in Various Biological Media[a]

	Predicted		
Media	Range	$\bar{x}$	Weighted[b] $\bar{x}$
Soil	0.001 – 1.1	0.19	0.08
Mushrooms	53.1 – 459	261	91.5
Plants	1.1 – 6.1	3.9	1.3
Insects	2.3 – 13	8.2	2.8
Carnivorous invertebrates	3.3 – 19.1	12.1	4.2
Mice	2.4 – 14.8	9.1	3.2
Deer mice	4.5 – 20.6	9.3	2.6
Voles	2.2 – 12.5	7.9	2.7
Shrews	6.1 – 34.6	21.8	7.6
Small birds	2.1 – 12.3	7.7	2.7
Estimated Using "Best Judgment" Percent of Onsite Foraging			
Kestrel diet	3.5 – 10.9	7.6	2.6
Kestrel egg[c]	5.3 – 24.3	15.0	5.2
Barn owl diet	3.7 – 12.3	8.4	2.9
Barn owl egg[d]	5.8 - 28.5	17.3	6.0
Shrike diet	4.4 – 16.4	11.0	3.8
Shrike egg[e]	7.3 – 41.8	24.7	8.6
Killdeer diet	3.7 – 13.9	9.2	3.0
Killdeer egg[f]	5.6 – 33.7	19.6	6.2
Estimated Using 100% Onsite Foraging			
Kestrel diet	4.6 – 17.4	11.7	4.0
Kestrel egg	7.7 – 45.4	26.7	9.3
Barn owl diet	4.3 – 15.8	10.6	3.7
Barn owl egg	7.0 – 39.7	23.5	7.0
Shrike diet	4.9 – 18.9	12.6	4.4
Shrike egg	8.3 – 50.7	29.6	10.4
Killdeer diet	4.8 – 22.0	14.1	4.5
Killdeer egg	8.2 – 61.9	34.6	10.9

[a] Based on LBNL predicted water-extractable soil selenium, and shown as using "best judgment" of onsite foraging for the species (based on Kesterson field data and published foraging ranges) and 100 percent onsite foraging
[b] Weighted by habitat type (13% Open, 31% Grassland, and 56% Filled)
[c] American kestrels were assumed to forage on-site 58%
[d] Barn owls were assumed to forage on-site 75%
[e] Loggerhead shrikes were assumed to forage on-site 85%
[f] Killdeer were assumed to forage on-site 60%

4.1.1.2 Aquatic Habitats

The model output produced predictions of the frequency of given bird use and average dietary concentrations. Figures 4-1, 4-2, and 4-3 show the potential bird use for each species for the months of interest (as predicted, based on the extent of ponding). The model also produced estimates of the expected frequency for various dietary selenium concentrations for the three species, which are shown in Figures 4-4, 4-5, and 4-6. Figures 4-5 and 4-6 also reflect inclusion of terrestrial components in the average diet concentrations for killdeer and mallards, respectively. April was not included in the model due to the extremely low probability of ponding (6 percent) of a small percentage of the Reservoir (< 10 percent). Bird use and dietary exposure were predicted from ponding and yielded non-existent risk for April conditions.

Estimation of risk based on selenium exposure required the prediction of selenium concentrations in eggs. Monitoring results for selenium concentrations in invertebrate and plant dietary items for birds were compared to egg selenium concentrations from the 1998 KRBMP data set to yield Kesterson-specific environmental transfer factors. (These site-specific transfer factors are relatively low because they do not represent true diet-to-egg transfers, which can be documented only if 100 percent of the birds' diets come from within the site and diet composition is well known. Thus, the transfer factors are referred to as "environmental transfer factors.") Extensive ponding and higher-than-normal bird use characterized the year 1998. In addition, we were able to collect a relatively large number of samples of aquatic invertebrates, terrestrial invertebrates, and terrestrial plants that could be used to estimate bird dietary selenium concentrations for the bird species in the model. The 1998 sampling year was of most value, however, because an unusually high number of semi-aquatic birds nested at Kesterson. The average egg selenium concentrations of black-necked stilts, killdeer, and mallards from 1998 were compared to estimated dietary selenium concentrations (from measured concentrations of selenium in aquatic invertebrates, terrestrial invertebrates, and terrestrial plants) to yield average environmental transfer factors for selenium. Based on 1998 data, the transfer factors for stilts, killdeer, and mallards were 0.57, 0.51, and 0.48, respectively.

Skorupa (1998) developed a relationship between black-necked stilt egg failures and egg selenium concentrations from a large database of egg chemistry and nesting success. We were able to use Skorupa's equation with our egg selenium concentration estimates (based on the above environmental transfer factors) to calculate the number of stilt hens with at least one probable egg failure, as follows:

Raw percentage of hens affected = exp(-2.327+0.0503 * Egg selenium conc.)/
(1+exp(-2.327+0.0503 * Egg selenium conc.)

Actual percentage of hens affected = [(1-background%) – (1-raw %)] / (1-background %)

Number of affected hens = (No. of birds counted/2) * Percentage of hens affected
where background % = 8.9%

The calculation was run as a function of the set of 1,000 estimated egg-selenium concentrations for both black-necked stilts and killdeer because of the similarities between the species. No such estimating technique was available for mallards. Although shorebirds may nest in April, April model results were not calculated because they show no exposure.

Kesterson is dry 94 percent of the time in April and shows minimal ponding in years of April flooding.

The probable number of hens affected by egg failure was estimated to exceed the background failure rate of about 8.9 percent (the calculated background failure rate for black-necked stilts) in a very limited number of cases. The model results indicated less than one killdeer hen would be affected by a loss of eggs due to selenium toxicity (0.1 – 0.3 hens affected). The results for black-necked stilts showed possible affected hens for the month of January only, with less than 3 hens affected. However, stilts typically begin nesting later in the season and therefore would rarely be affected. Similarly, the weighted mean selenium concentrations in killdeer eggs predicted by the terrestrial food chain model indicate that the percentage of hens affected (based on purely terrestrial exposure routes), would be less than the background failure rate of 8.9 percent.

4.1.2 Qualitative Evaluation

Kesterson Reservoir has been managed over the past 10 years as a terrestrial habitat. Terrestrial exposure to the selenium inventory of the Reservoir has not resulted in demonstrable effects on local wildlife and is not expected to cause such effects in the future.

The overall summary of selenium exposure from the ephemeral pool habitats at Kesterson Reservoir suggests insignificant risk to waterfowl and shorebirds. In most cases, ponding is too limited to represent significant exposure. In the rare cases when ponding persists, a very small number of birds (one or two) may be adversely affected a small percentage of the years (less than 5 percent).

4.2 Risk Description

The evaluation of ecological risk from seleniuim exposure in the terrestrial and aquatic environments at Kesterson Reservoir is based on several lines of evidence. We have evaluated risks based on a long-term record of water-extractable soil selenium and extensive records of waterborne and bird dietary selenium concentrations, combined with an overall low frequency of ponding and the infrequent persistence of ephemeral pools for 1 month or more during the bird nesting season. Risks associated with the ephemeral pools were strongly determined by the balance between exposure (the degree of ponding at critical seasons during the year) and the spatial variation of both waterborne selenium concentrations and bird use. In particular, bird use was the single most important direct determinant of risk. Although the water and invertebrate fauna of ephemeral pools contain relatively elevated selenium concentrations, risk is most often minimized through the limited ponding and lack of pool use by birds.

There is uncertainty in the modeled predictions of bird use and pool concentrations, but the modeled concentrations and predictions of impairment frequency closely match observed data. As predicted by the model, only a small number of birds are expected to be adversely affected from selenium concentrations in their diet. Monitoring data over the past 12 years have not shown evidence of reproductive impairment to birds nesting at Kesterson attributable to selenium toxicity.

4.3 Uncertainties/Data Limitations

There are uncertainties and limitations at all levels of this analysis, as is typical of all ecological risk assessments. In this section, we describe the sources of uncertainty and specific limitations of the data and analysis.

4.3.1 Available Data

The Kesterson Reservoir database of selenium concentrations in various media, climatic variation, extent of ponding, and bird use is unusually comprehensive for an EcoRA. Rather than the typical 1 or 2 years of data, most of the summary statistics for selenium are based on 10 to 12 years of data gathered over a full range of seasons and inter-annual climatic variation. The climate record is based on 127 years of precipitation and estimated evapotranspiration data, incorporating periods of extended drought as well as extreme flooding (such as the 1997-1998 El Niño year). However, in some cases, such as data associated with the aerial photographic record, data sets are more limited. Ranges and measures of variability are presented with individual data summaries and regression relationships in the appropriate sections of this report.

It is unclear why the detected rates of egg inviability in killdeer (the most frequently sampled species; 4.3 percent of nests containing at least one fail-to-hatch [FTH] egg) are somewhat lower than background (8.9 percent of black-necked stilt nests containing at least one FTH egg), as reported by Skorupa (1998). Since Kesterson Reservoir was filled in 1988, the KRBMP has found seven inviable eggs in the 209 nests that were located during the monitoring. In general, nests were monitored on a weekly basis after they were found and marked. However, eggs in many of those nests were lost to predation, desertion, or destruction of nests (e.g., road grading) before they hatched, and from 1996 – 1999, when 64 percent of the eggs were collected, over 50 percent of the nests were lost. Therefore, it was not possible to determine accurately the rate of egg inviability in killdeer. In 1998, when 21 killdeer and 16 black-necked stilt eggs were collected at Kesterson and incubated in the laboratory at UC Davis, there were no killdeer eggs in which embryos died before hatching and there were two stilt eggs in which embryos did not develop (12.5 percent). In addition, 41 eggs were collected for examination and selenium analysis, no dead embryos were found in any of those eggs. Thus, it has not been possible to establish relationships between egg-selenium concentrations and reproductive impairment in killdeer, or to document the incidence of egg inviability (due to the high rates of eggs being lost to predation, or perhaps other confounding factors).

4.3.2 Analytical Techniques and Modeling Assumptions

Analytical techniques used in the terrestrial and aquatic habitat models are based on a series of linear and log-linear relationships among environmental variables. In each case, assumptions were made about the underlying distribution of the data and the appropriateness of the regression relationship in explaining covariance of the variables. Individual regression equations and bivariate plots are presented in the appropriate sections in this report. As is to be expected from environmental monitoring data, there is much unexplained variation in predictions, even in cases of statistically significant relationships. However, the basic assumption of the EcoRA models is that the predictive relationships are all descriptive of underlying causal relationships.

The EcoRA models are based on Monte Carlo simulations of the distribution of selected input variables. In this case, the underlying assumption is that the true distribution of the environmental variable can be accurately duplicated using random numbers sets generated from the mean, standard deviation, and assumed type of distribution of the monitoring data. Most simulated variables (annual extent of ponding, dietary concentrations, bird use) were based on log-normal relationships.

SECTION 5

Conclusions

As a result of this study, several summary conclusions can be made in relation to soil chemistry, the transfer of soluble selenium to surface water pools, and the extent of ponding on the Reservoir:

- Anticipated future soluble (i.e., bioavailable) soil selenium levels will fall within the range of concentrations observed over the last decade of soil selenium monitoring and research.
- The overall values for soil-to-ephemeral pool transfer of selenium are not expected to change in the future and can be predicted within a factor of 2 based on historical data.
- A ponding model based on the historic (127-year) Kesterson-area rainfall record predicts that in 43 percent of wet seasons, ephemeral pools will not form, or if they do form, they will have a duration of less than 1 month. Ponding for 2 months (needed to cause the development of invertebrate pond fauna) is expected to occur in approximately 11 percent of wet seasons. Ponding for 3 or more months is estimated to occur in about 37 percent of wet seasons.
- During the period of spring waterfowl and shorebird nesting, the ponding model predicts that there is a high probability (57 percent to 94 percent, depending on the month) that less than 1 percent of Kesterson Reservoir will be ponded.
- Ponding during the winter and spring of 1997-1998 represented the maximum ponded condition in the historical record and the near worst-case condition, in terms of modeling results for the extent of ephemeral pools.

The terrestrial habitats portion of the Ecological Risk Assessment model yielded the following conclusions:

- Selenium concentrations in the terrestrial food chain will continue to be elevated above normal, background-site levels.
- The terrestrial bird species modeled (American kestrel, barn owl, loggerhead shrike, and killdeer) will continue to exhibit egg selenium concentrations below those expected to cause reproductive effects but above background levels.
- Dietary selenium for the modeled species is below the level at which muscle wasting effects were observed in kestrels.
- Predicted selenium concentrations are below levels that are known to cause health or reproductive effects in small mammals under field conditions.
- Selenium concentrations in mushrooms will remain a potential source of ecological effects to the terrestrial food chain, in years that they occur.

The ephemeral pool portion of the Ecological Risk Assessment model yielded the following conclusions:

- Predicted selenium concentrations in bird dietary items (composed of aquatic invertebrates, terrestrial invertebrates, or terrestrial plants) exceeded dietary levels of concern for reproductive impairment in black-necked stilt and killdeer, and exceeded levels of concern 16 to 43 percent of the time for mallards. However, no evidence of toxicological impact has been observed for these species during the 12 years of the Kesterson Reservoir Biological Monitoring Program, including results for 1997-1998, the year of highest observed ponding at Kesterson.
- Daily bird use during the months of concern, based on the extent of ponding, was predicted to be less than 20 birds more than 90 percent of the time for black-necked stilt, killdeer, and mallard.
- The average number of black-necked stilt and killdeer hens expected to have one more eggs fail to hatch due to elevated selenium exposure through the Kesterson Reservoir ephemeral pools was expected to be fewer than two hens for 99 percent of modeled years.

SECTION 6

Recommendations

6.1 Recommendation 1

Fill the low-lying areas of the Reservoir in which ephemeral pools form on an annual basis due to rising groundwater. Most of these areas are found along the eastern boundary of Ponds 1, 2, and 5; others include several small former Experimental Areas. The location and size of these pools can be identified from the aerial photographs obtained in February 1999. These pools occupy an estimated 0.05 percent of the Reservoir (1 acre).

6.1.1 Purpose:

Reduce exposure to aquatic environments with the highest selenium concentrations.

6.1.2 Rationale:

These pools form nearly every year and typically have selenium concentrations exceeding several hundred micrograms per liter. Filling these pools will eliminate aquatic exposure pathways during dry years. In wet years, it will reduce exposure to pools with the highest concentrations of selenium.

6.2 Recommendation 2

Conduct biological monitoring in 2001 to include the following: mushrooms (if they are available in 2001), dominant plants (a grass, forb, and perennial in each trisection), terrestrial invertebrates (pitfall invertebrates and grasshoppers), small mammals (10 deer mice from each trisection and plus up to 10/trisection each of house mice, harvest mice, voles, and shrews that are captured during deer mouse trapping), bird eggs (killdeer, stilts if it is a wet year, shrike, kestrel, and barn owl). In addition to analyzing all samples for selenium, analyze plants, invertebrates, and bird eggs also for boron. After 2001, conduct monitoring of selenium in a reduced subset of biota types (plants and bird eggs listed above) in 2006 and 2011. Then determine whether conditions are stable and biological monitoring can be discontinued. Monitor selenium in the standard ephemeral pool set on the same schedule (2001, 2006, and 2011 wet seasons), as well as on the high rainfall years specified in recommendation 3, below.

6.2.1 Purpose:

To document "current conditions" in the base year of 2001, and also provide confirmation of status of boron exposures for birds.

6.2.2 Rationale:

The selected types of biota will provide adequate verification of selenium status in plants and animals 3 years after the El Niño event (and before a change in the monitoring program,

since the last complete suite of samples was from 1998), and for a reasonable time into the future (another decade). The USFWS raised concerns about boron in their comments on the draft EcoRA, and analyzing selected biota will help to determine whether boron also should be a COPEC for future monitoring.

6.3 Recommendation 3

Obtain water quality and biota (invertebrates) samples from ephemeral pools when the cumulative rainfall minus 0.89*cumulative ET_o is greater than 10 cm. Weekly evaluation of cumulative rainfall minus 0.89*cumulative ET_o should provide early warning that monitoring may be needed. The CIMIS station at Kesterson should be maintained for obtaining these data.

6.3.1 Purpose:

Verify that selenium concentrations in ephemeral pools and aquatic invertebrates during extremely wet years are consistent with the risk assessment and also to evaluate the effects of having filled the low-lying areas where pools now form by groundwater.

6.3.2 Rationale:

Water quality and biota samples should be obtained from ephemeral pools when "significant" ponding occurs at Kesterson. We suggest that "significant" be defined as years when greater than 30 percent of Kesterson is ponded during the nesting season. Observations at Kesterson indicate that 30 percent of Kesterson is likely to be ponded when cumulative rainfall minus 0.89*cumulative ET_o is 10 cm. Analysis of meteorological data from Kesterson indicates that this will occur 10 percent of years by February 28, and 5 percent of years by March 31. We therefore suggest that when cumulative rainfall minus 0.89*cumulative ET_o is greater than 10 cm, water quality and biota samples should be collected from ephemeral pools beginning in late February. If pools persist into March, April or May, we suggest monthly sampling until they are gone.

6.4 Recommendation 4

Obtain soil samples at the long-term monitoring sites (e.g. biological sampling sites and standard ephemeral pool sites) every 5 years, beginning in 2001.

6.4.1 Purpose:

Verify that total and water extractable selenium concentrations in soils are consistent with the values used in the risk assessment.

6.4.2 Rationale:

Analysis of over a decade of data on extractable and total selenium concentrations in the top 15 cm of soil has shown that selenium concentrations have remained relatively stable over this period. Nevertheless, a slow oxidation to more soluble forms may occur at rates in the range of 0 to 2 percent per year. Soil sampling at a frequency of once every 5 years will provide information to confirm that the rate of change is as slow as has been observed over

the past decade. Under very dry conditions the net selenium oxidation rate may reach around 2 percent per year. If those conditions persist for 5 years, the net increase in soluble selenium concentrations would be 10 percent, a difference that can be analytically detected and statistically discerned. Therefore, the 5-year sampling interval would provide the opportunity to observe changes under the most conservative selenium transformation scenario. In addition to analyzing the samples for water-extractable and total selenium, more comprehensive speciation and fractionation of selenium should be obtained from a small subset of the samples collected during the 5-year sampling effort. This will serve to verify that the underlying assumptions regarding speciation of selenium remain consistent with the assumptions used in the risk assessment.

6.5 Recommendation 5

Continue monitoring groundwater levels at key locations in the Reservoir on either a semi-annual or continuous basis. Electronic pressure monitoring and telemetric data transmission may be utilized if found to be cost-effective. This effort may involve between 5 and 15 wells. Reduce groundwater sampling and analysis frequency to once every 5 years.

6.5.1 Purpose:

Continue to provide a record of water table elevation. Monitor the groundwater plume.

6.5.2 Rationale:

Low-cost groundwater level monitoring will provide a valuable record of water table fluctuations, which may affect the formation of ephemeral pools. Past records form an important database, which has been used not only to interpret the formation of some ephemeral pools but also to correlate changes in regional hydrology. Groundwater quality records from the last 10+ years show that the groundwater plume, as conservatively defined by boron concentrations, is very slow-moving, with no discernible front displacement over that period. Therefore, a 5-year sampling frequency is adequate to track the movement, if any, of this plume.

6.6 Recommendation 6

Pursue an arrangement that would facilitate long-term monitoring of wildlife and research at the site. This could be accomplished by developing a partnership with an academic, non-profit, or other entity for continued long-term monitoring of Kesterson biota that will identify changes in animal populations, encourage academic research, and allow periodic selenium monitoring as needed. This type of management could be provided by an organization such as the non-profit Center for Land Management that manages mitigation lands and has a mission of long-term population monitoring and support of research, or the University of California, or some other organization.

6.6.1 Purpose:

Selenium concentrations in the various biota sampled at Kesterson continue to be elevated over background and reference levels. Also, the existing database at Kesterson is unique and offers unique opportunities for understanding of selenium ecotoxicology.

6.6.2 Rationale:

Monitoring of selenium concentrations in biota at Kesterson has shown that selenium concentrations have remained elevated but relatively stable over the past decade. This monitoring has also provided information on local bird and small mammal populations and their cycles. Kesterson continues to offer opportunities for further advances in understanding selenium ecotoxicology and wildlife populations in the Central Valley. The academic or non-profit entity that is selected to manage Kesterson should have a mission that includes long-term monitoring of wildlife populations and support of research. This would provide important background information to be used during the event-triggered and periodic monitoring of Kesterson.

SECTION 7
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Figures

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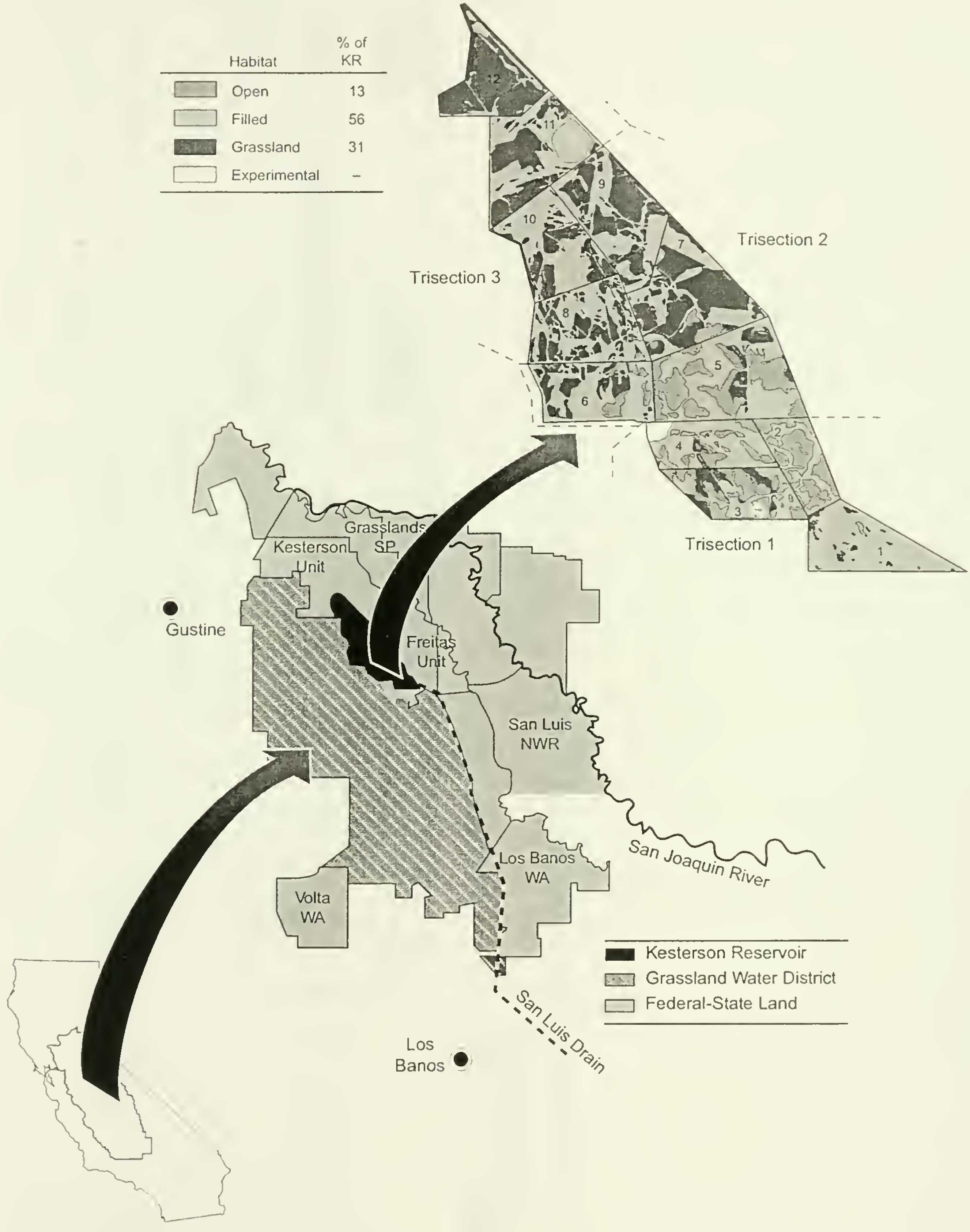


Figure 1-1
Kesterson Reservoir Location and Habitats

CH2MHILL

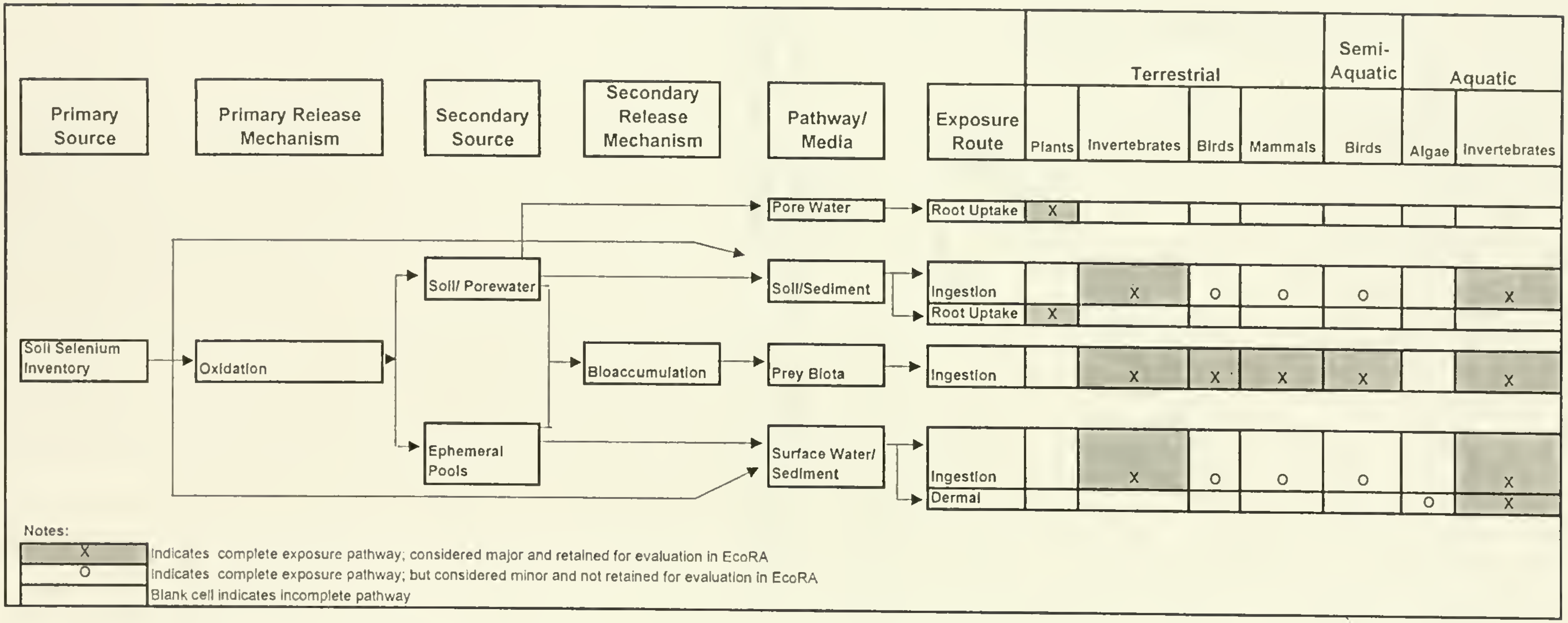


Figure 2-1. Conceptual Site Model, Kesterson Reservoir Ecological Risk Assessment

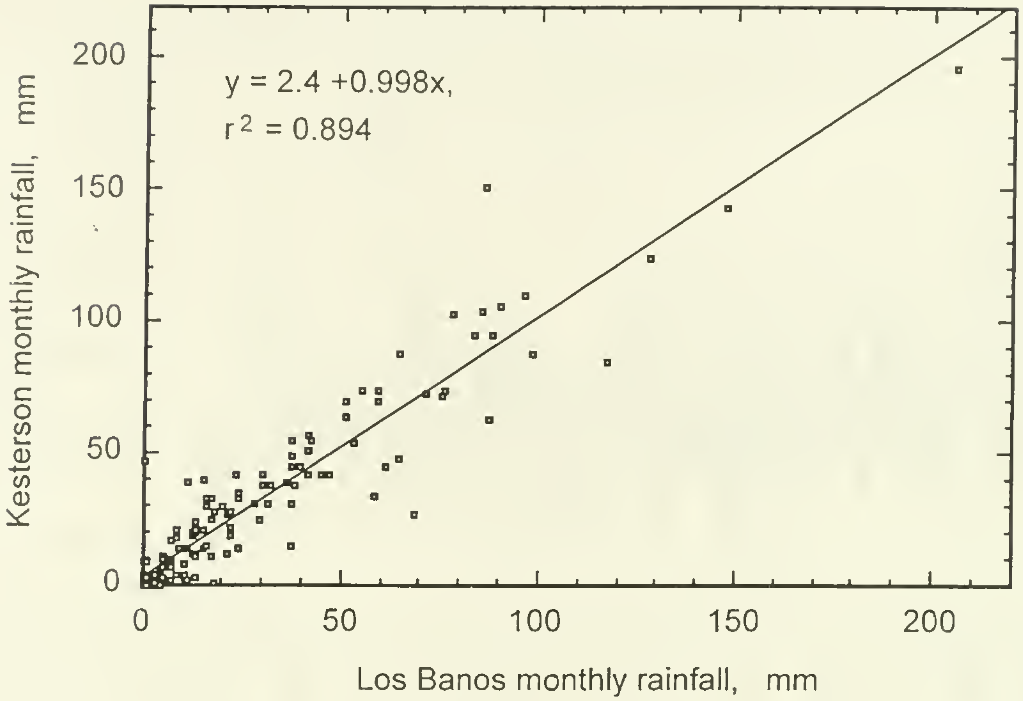


Figure 2-2. Correlation between monthly rainfall at Los Banos and at Kesterson Reservoir, 1985 through 2000.

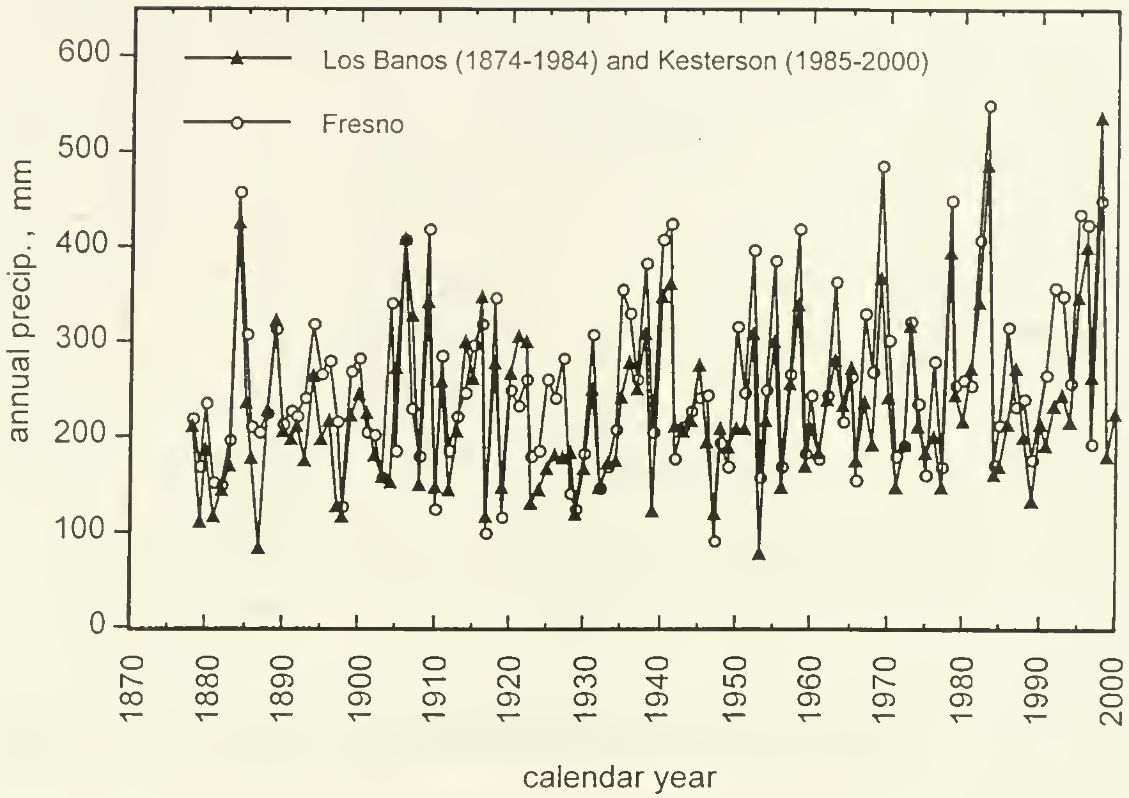


Figure 2-3. Annual rainfall record for Los Banos, Kesterson, and Fresno.

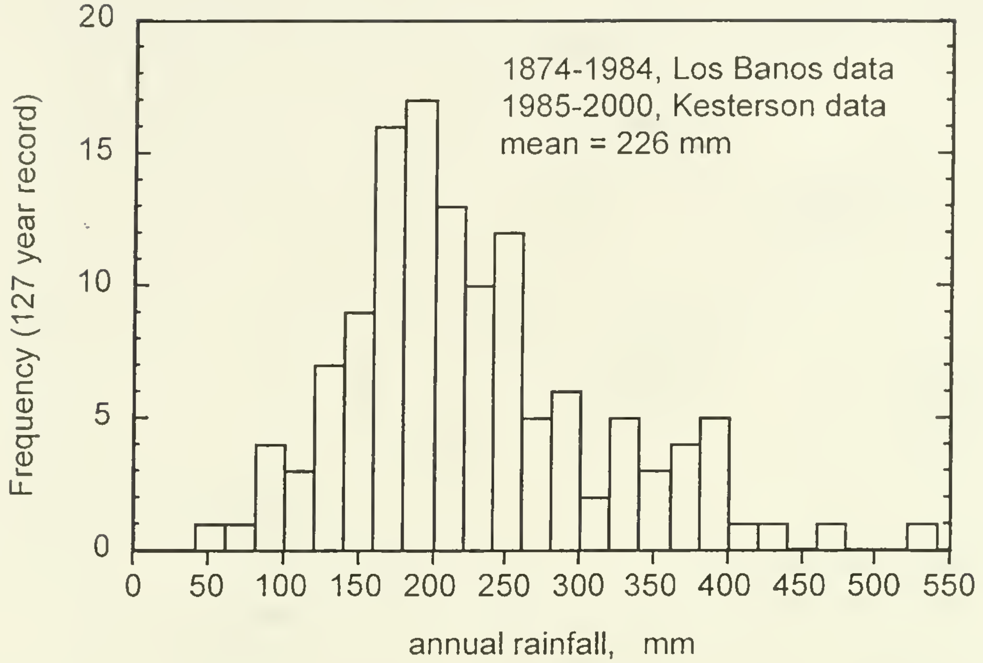


Figure 2-4. Frequency distribution of annual rainfall.

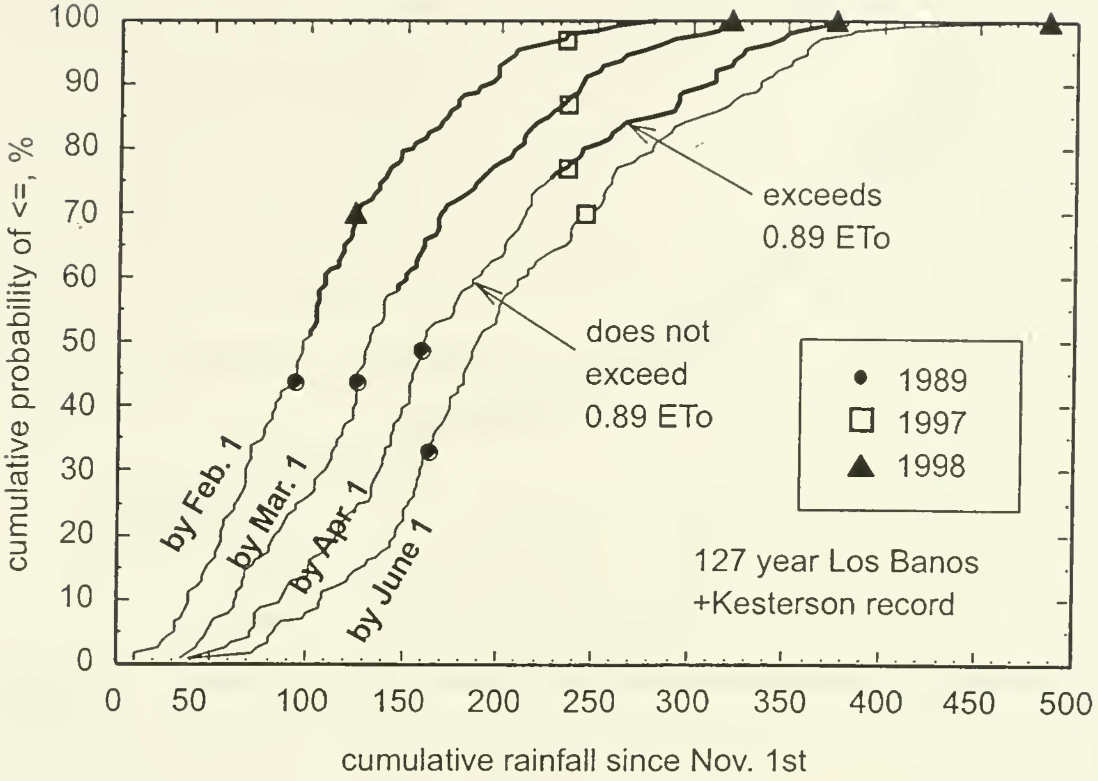


Figure 2-5. Cumulative probability of exceeding seasonal cumulative rainfall = x mm by February 1st, March 1st, April 1st, and June 1st. Cumulative rainfall from the 1989 (drought), 1997 (above average), and 1998 (El Nino) years are indicated on monthly curves. Also shown for later reference are segments along the cumulative rainfall probability curves that do not (lighter trace), and that do (darker trace) exceed 0.89 times the cumulative average ETo.

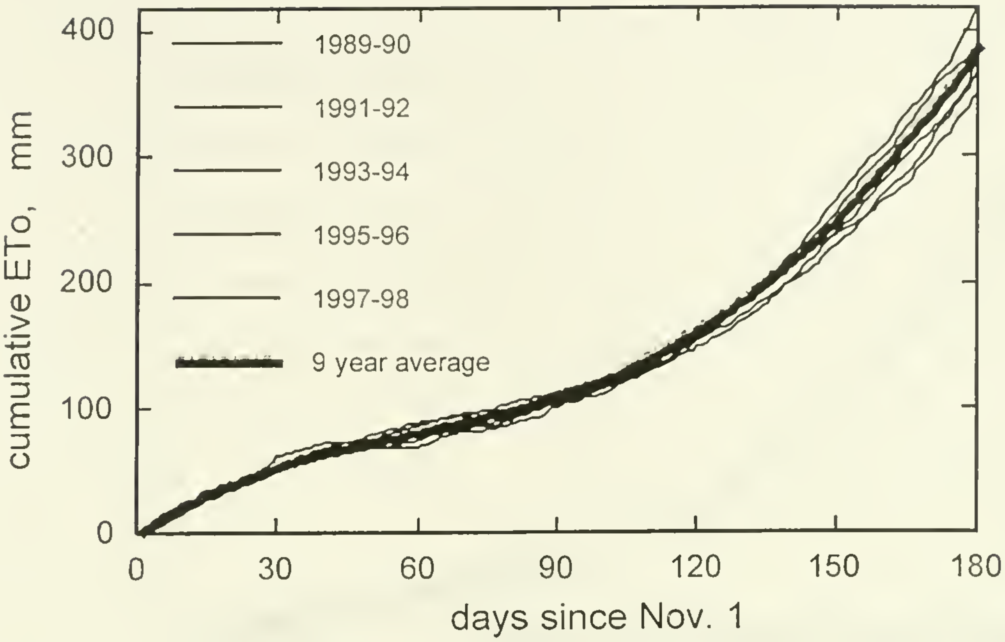


Figure 2-6. Cumulative ETo trends for various wet seasons at Kesterson Reservoir.

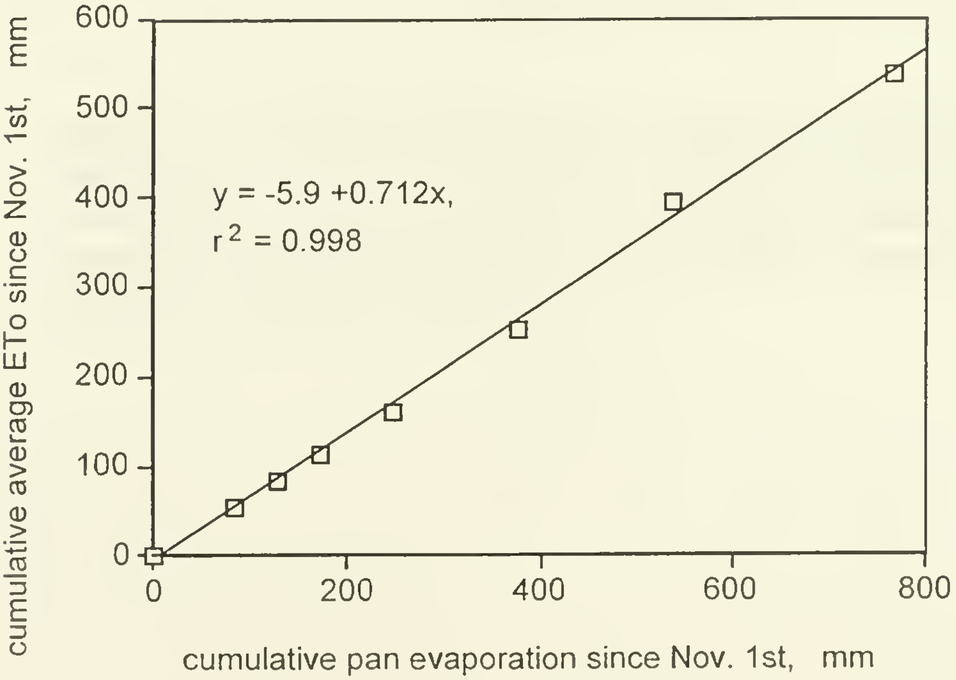


Figure 2-7. Correlation between cumulative monthly pan evaporation measured at Kesterson Reservoir and cumulative average monthly ETo, for the months of November through May.

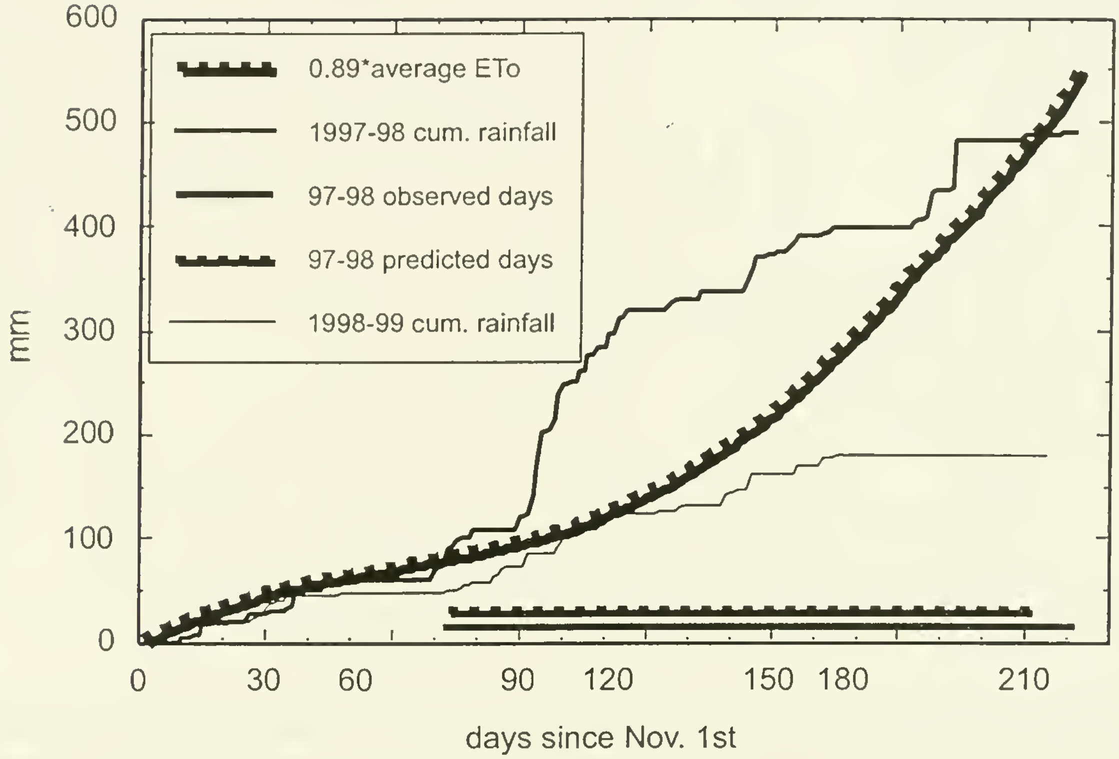


Figure 2-8. Simplified prediction of ponding during the 1997-98 and 1998-99 wet seasons. Ponding is predicted when the cumulative precipitation curve exceeds the cumulative 0.89xETo curve. Negligible ponding was observed in 1998-99, whereas extensive ponding occurred in 1997-98.

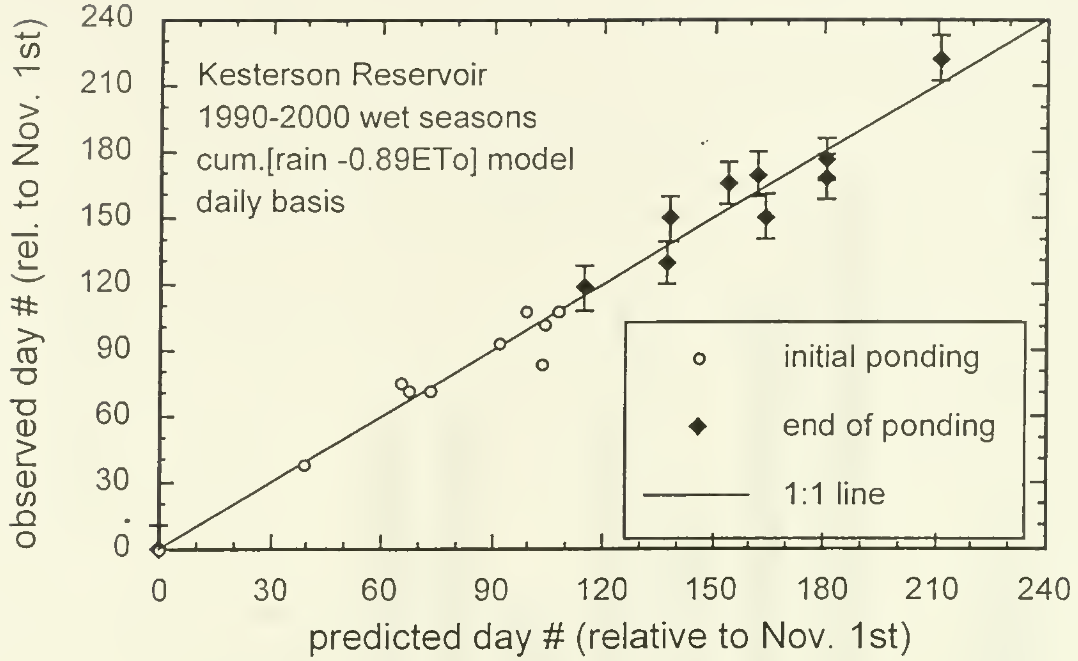


Figure 2-9. Predicted versus observed days for initial ponding and cessation of ponding for the years listed in Table 2-2 where ponding is predicted.

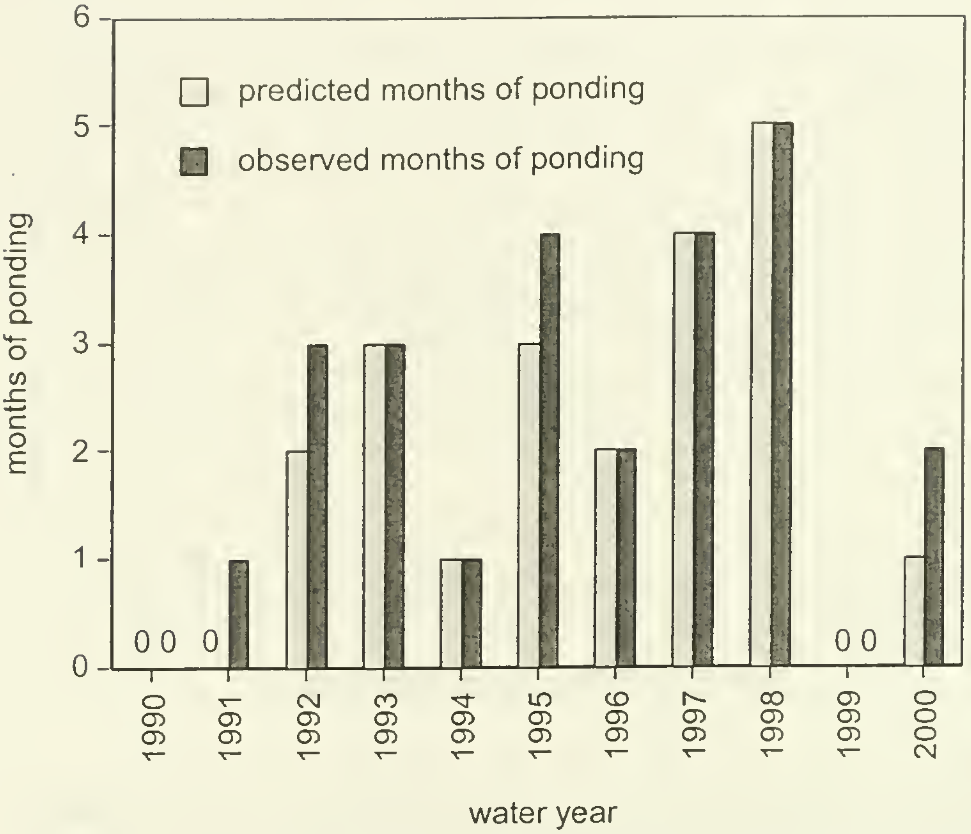


Figure 2-10. Comparison between predicted versus observed duration of ephemeral pool formation, based on monthly weather data.

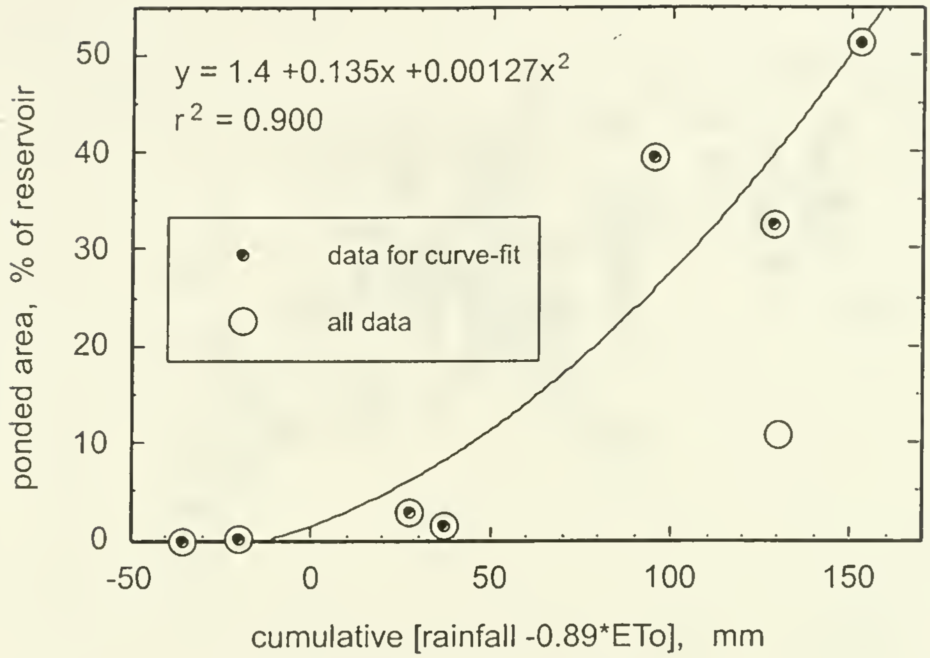
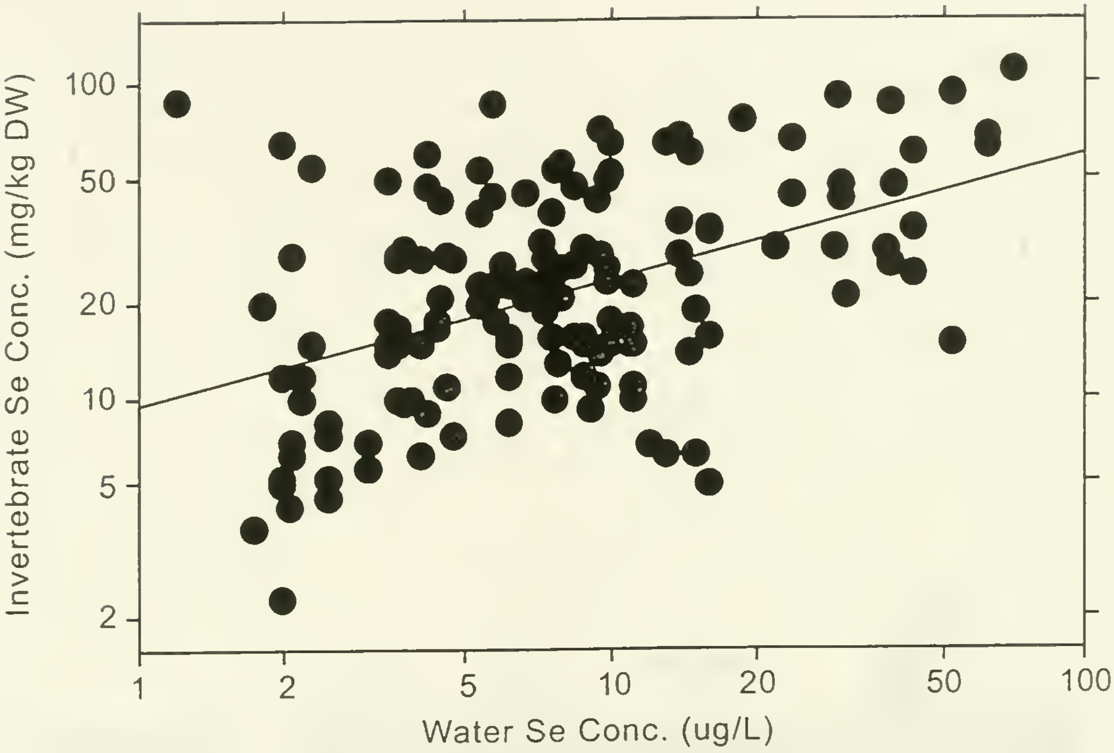


Figure 2-11. Aerial photograph-based estimates of percent areal ponding at Kesterson Reservoir, correlated to cumulative [rainfall - 0.89 *ETo]. This fit is optimized to minimum root mean square deviation, excluding the single point (shown) that would yield low predicted areal ponding.



Y = 0.986 + 0.393 * (LogWater Se Conc., ug/L); R^2 = 0.199

Figure 2-12. Aquatic invertebrate: water relationship, Kesterson Reservoir ephemeral pools.

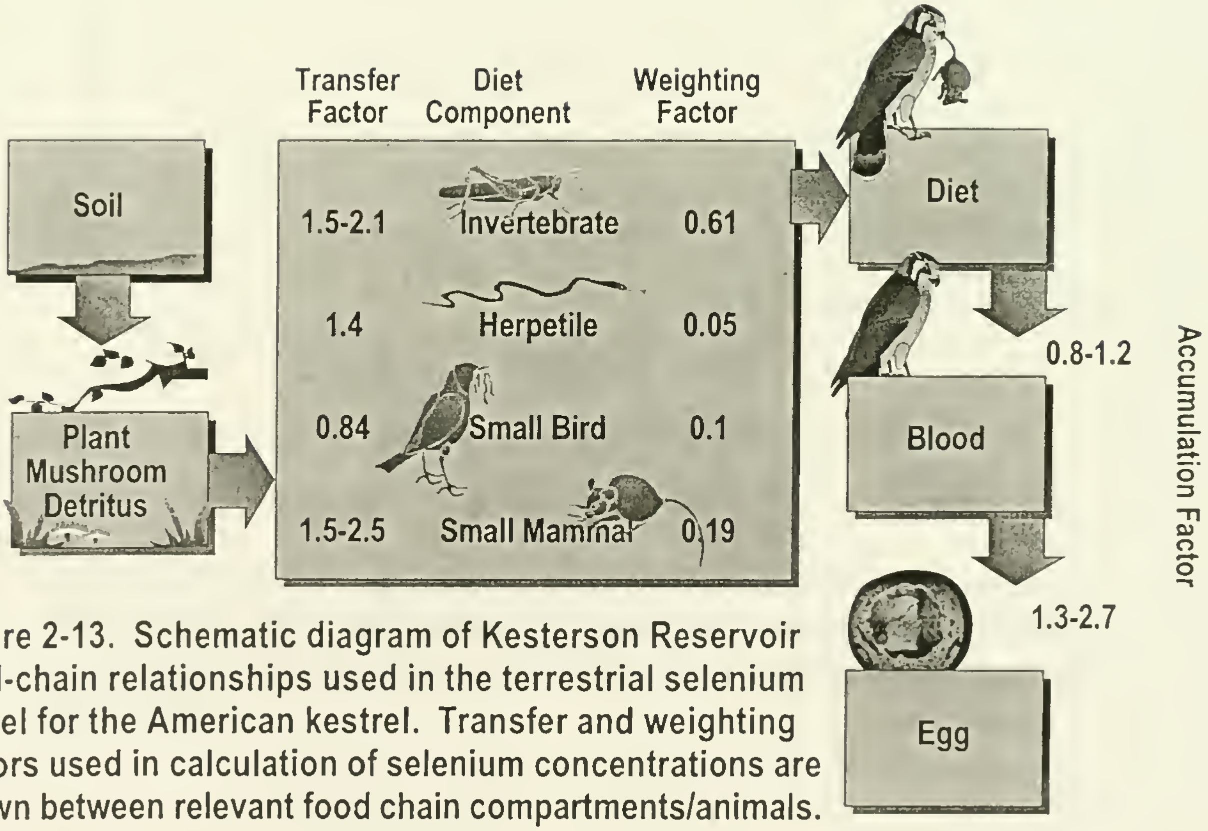


Figure 2-13. Schematic diagram of Kesterson Reservoir food-chain relationships used in the terrestrial selenium model for the American kestrel. Transfer and weighting factors used in calculation of selenium concentrations are shown between relevant food chain compartments/animals.

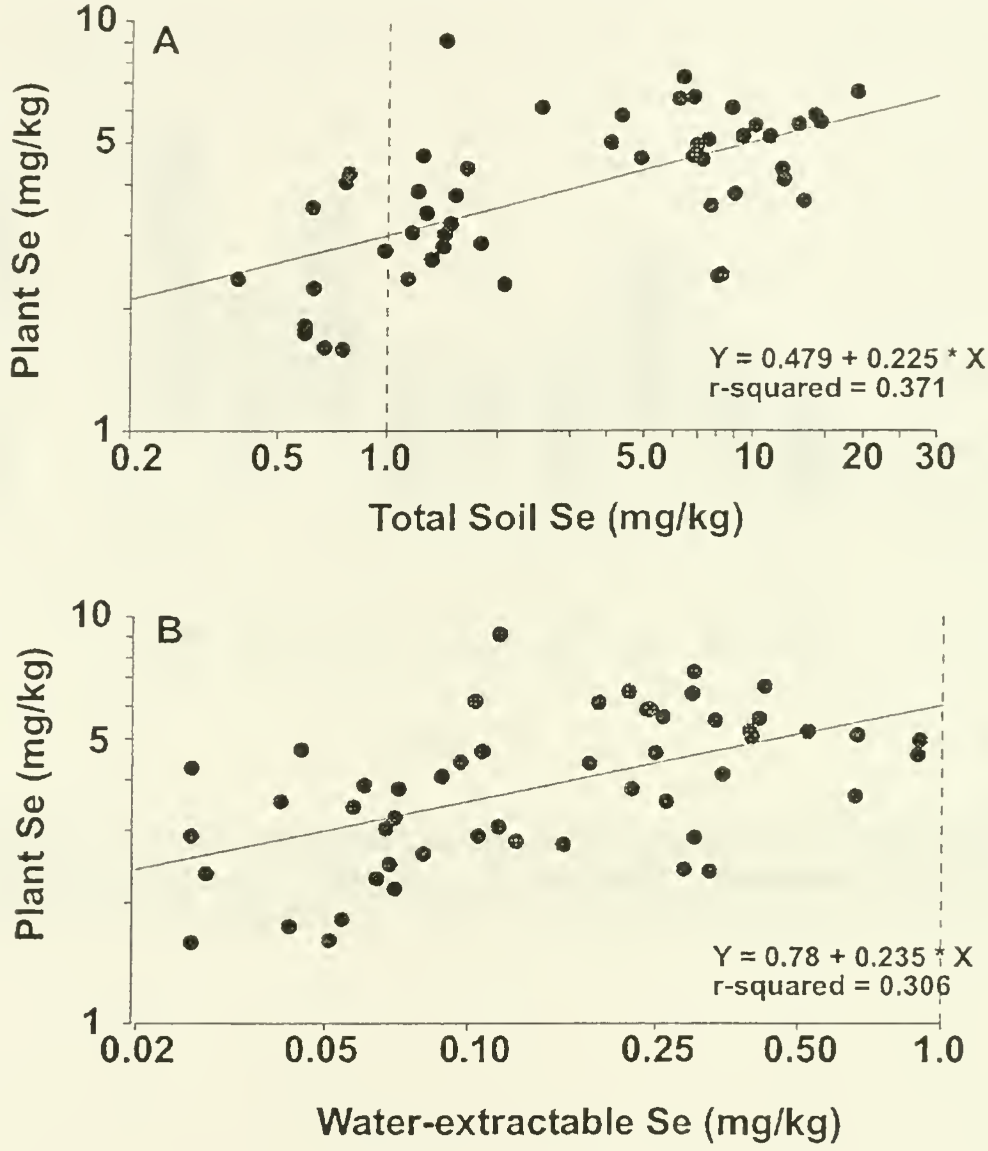


Figure 2-14. Log-log relationship between plant selenium concentrations (mg/kg) and total soil selenium (A) and water-extractable selenium in soil (P< 0.001 for both) at Kesterson, 1989-1994.

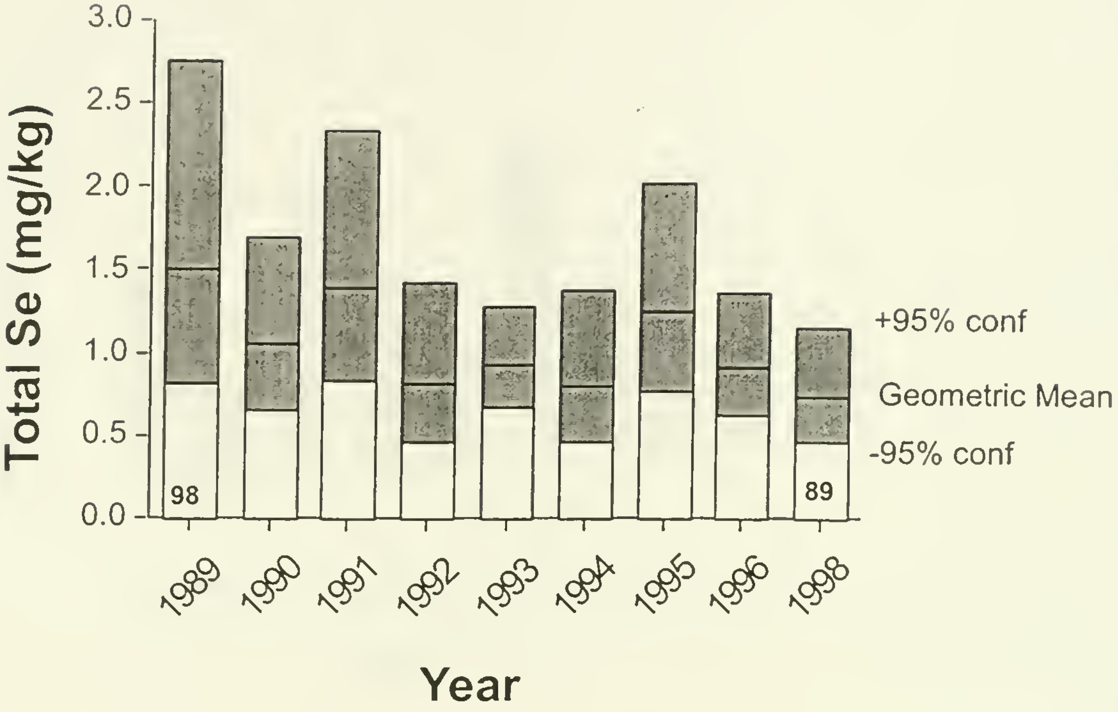


Figure 3-1. Total selenium concentrations in the top 15 cm of soil in the Filled habitat. Years that were significantly different at the 95% confidence level shown for each year.

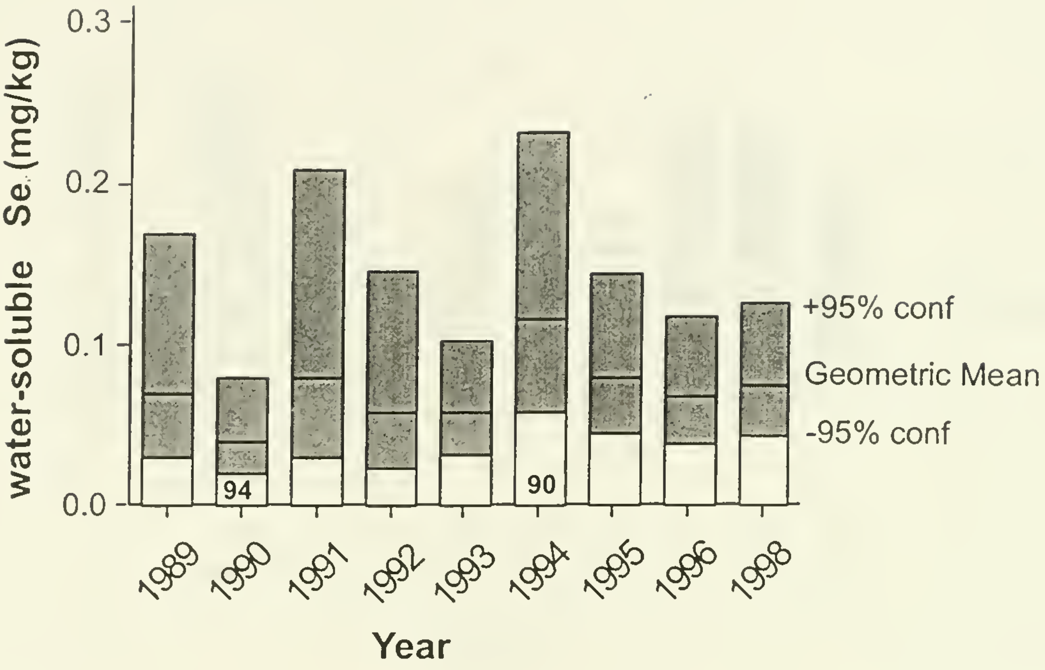


Figure 3-2. Water-soluble selenium concentrations in the top 15 cm of soil in the Filled habitat. Years that were significantly different at the 95% confidence level shown for each year.

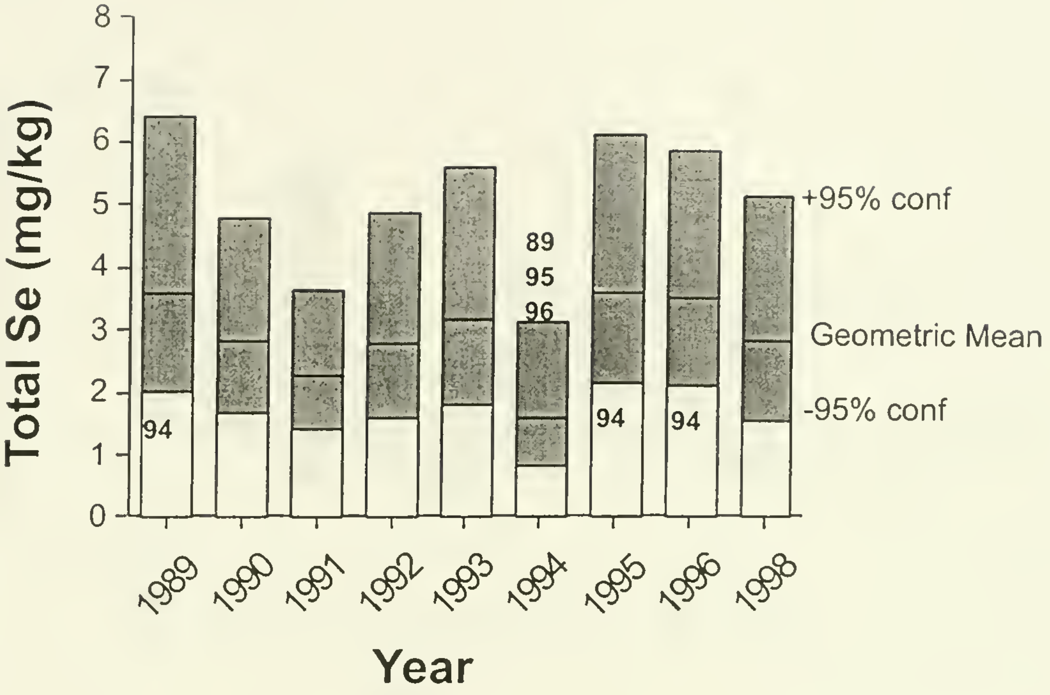


Figure 3-3. Total selenium concentrations in the top 15 cm of soil in the Grassland habitat. Years that were significantly different at the 95% confidence level shown for each year.

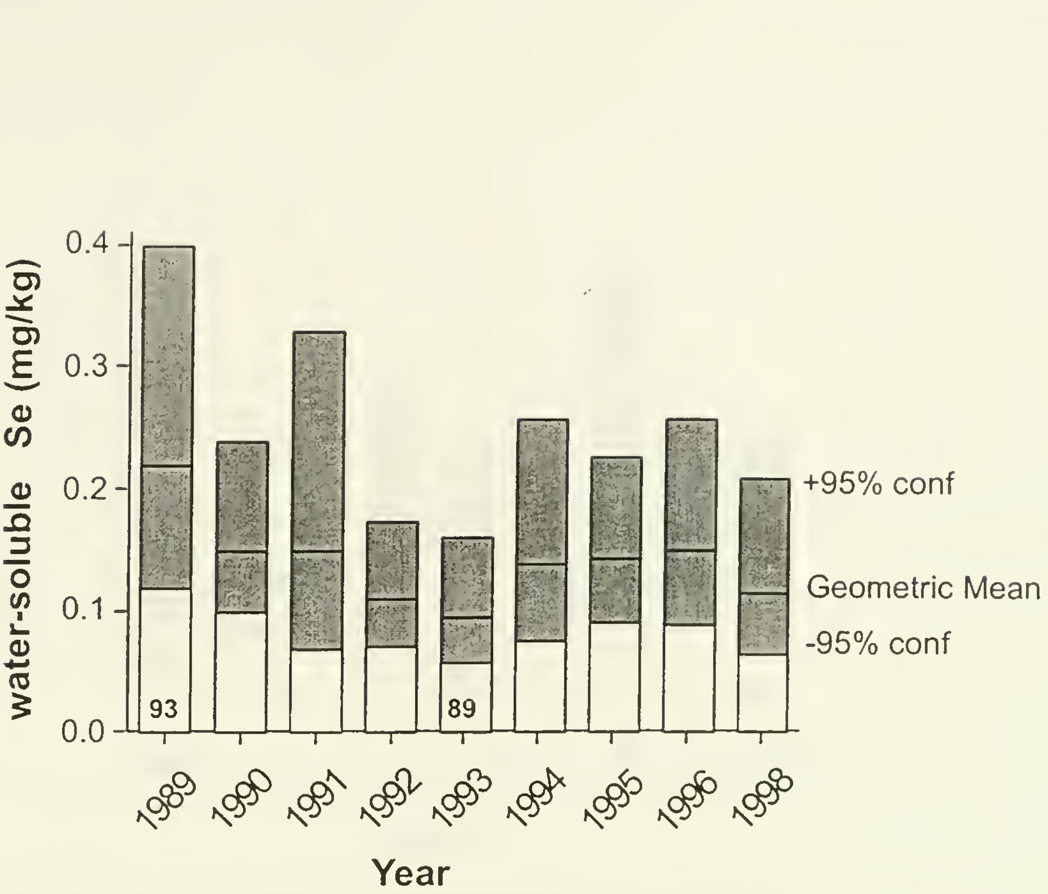


Figure 3-4. Water-soluble selenium concentrations in the top 15 cm of soil in the Grassland habitat. Years that were significantly different at the 95% confidence level shown for each year.

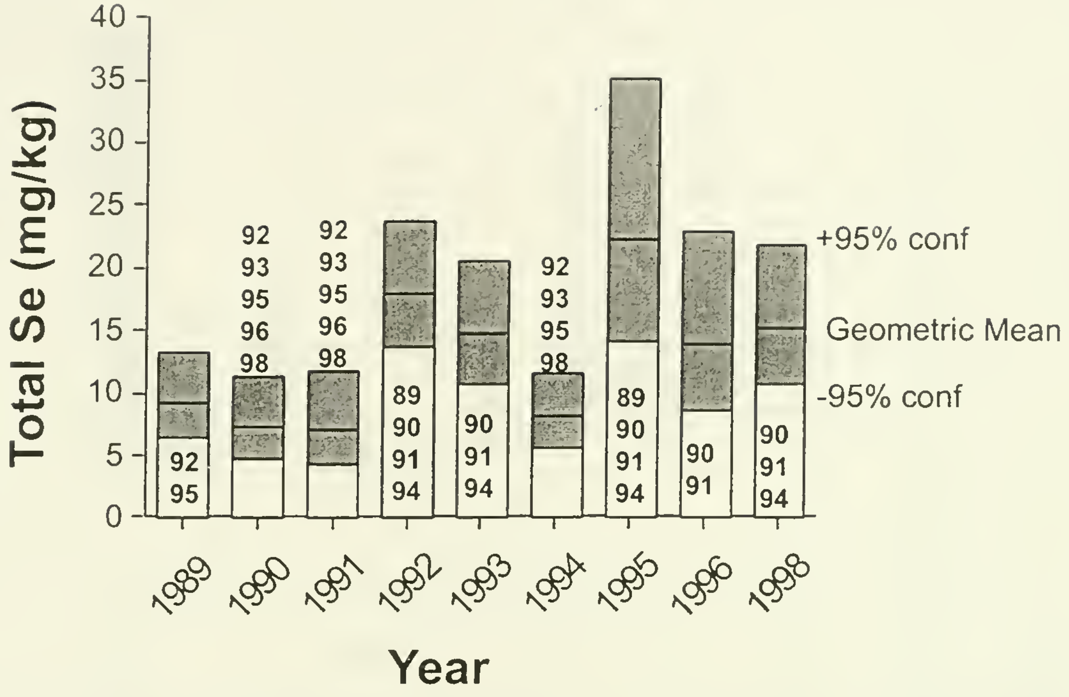


Figure 3-5. Total selenium concentrations in the top 15 cm of soil in the Open habitat. Years that were significantly different at the 95% confidence level shown for each year.

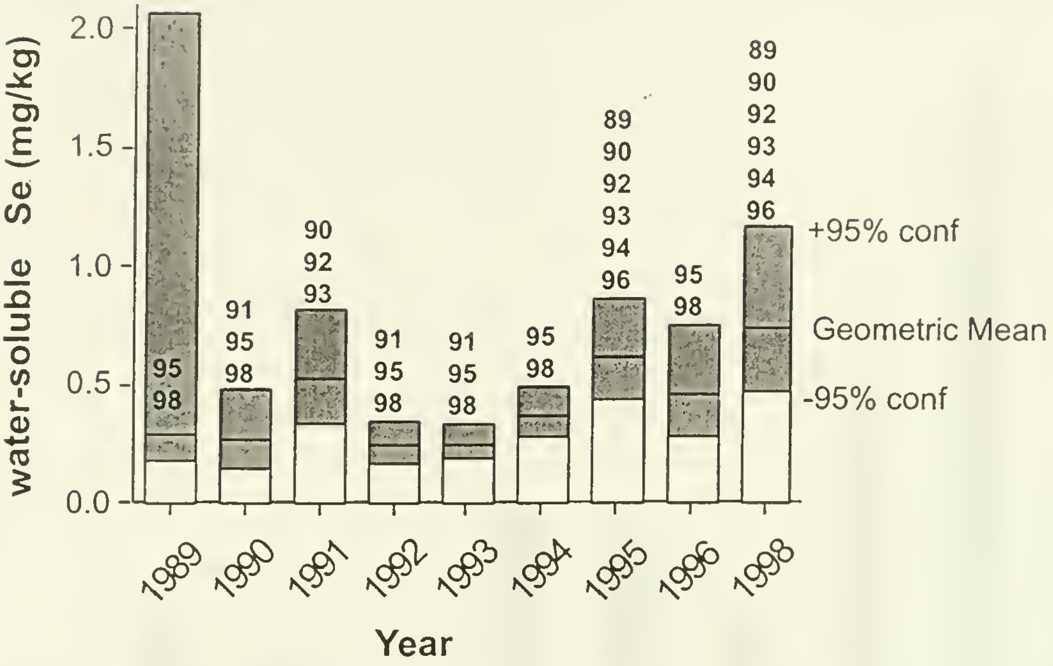


Figure 3-6. Water-soluble selenium concentrations in the top 15 cm of soil in the Open habitat. Years that were significantly different at the 95% confidence level shown for each year.

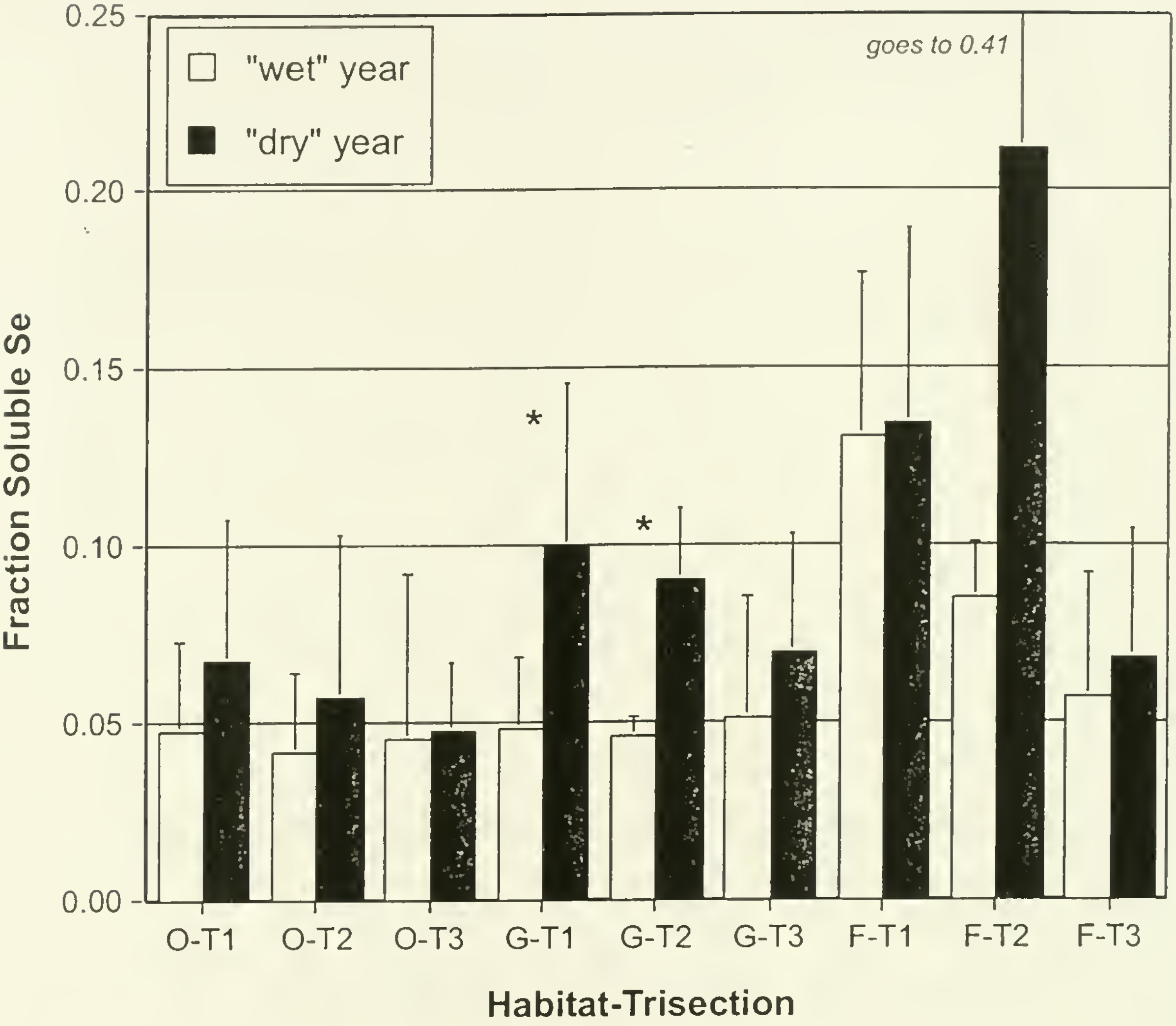


Figure 3-7. Fraction soluble selenium in surface (0-15 cm) soil during "wet" and "dry" years, by habitat and trisection. Cases that were significantly different at the 95% confidence level are marked with an asterisk.

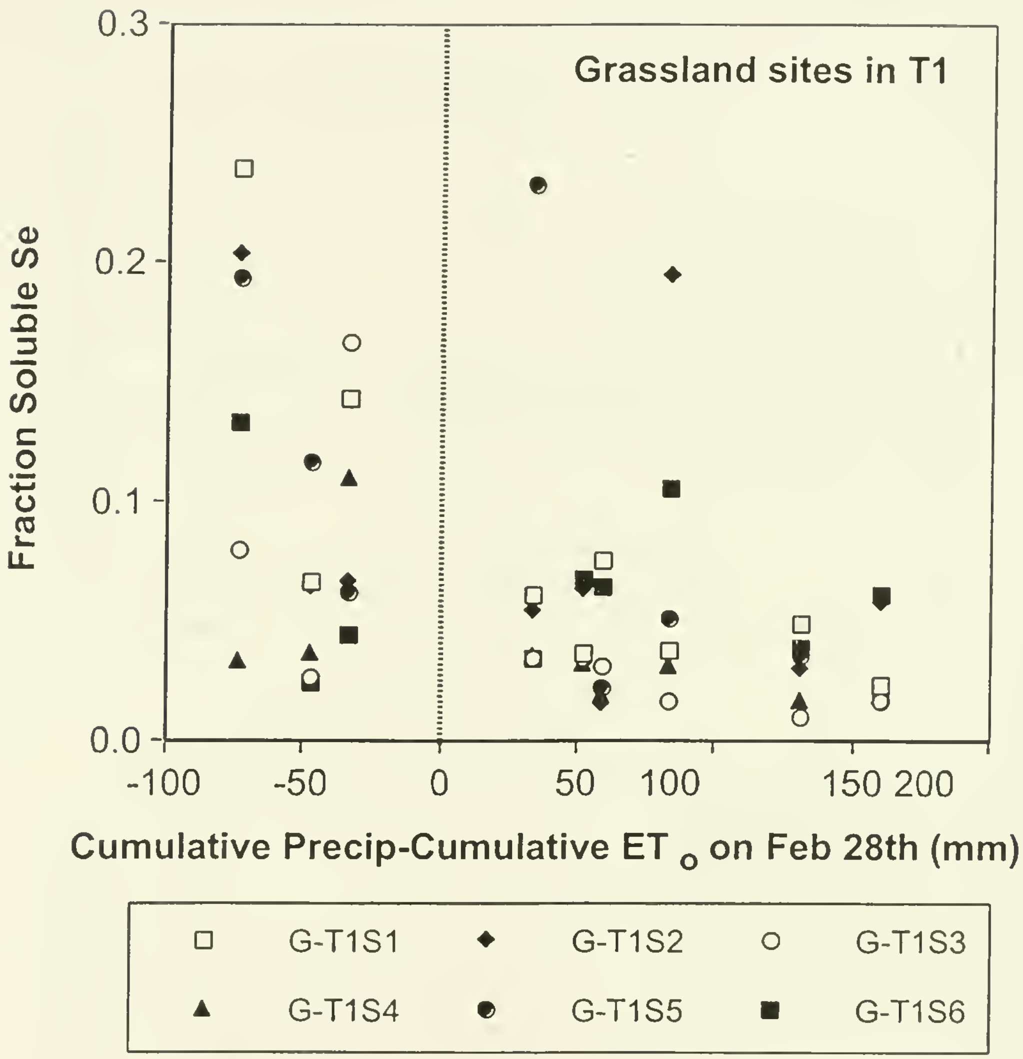


Figure 3-8. Fraction soluble selenium between 1989 and 1998 at Grassland habitat sites in Trisection 1. The vertical line at zero defines "wet" years on the right and "dry" years on the left.

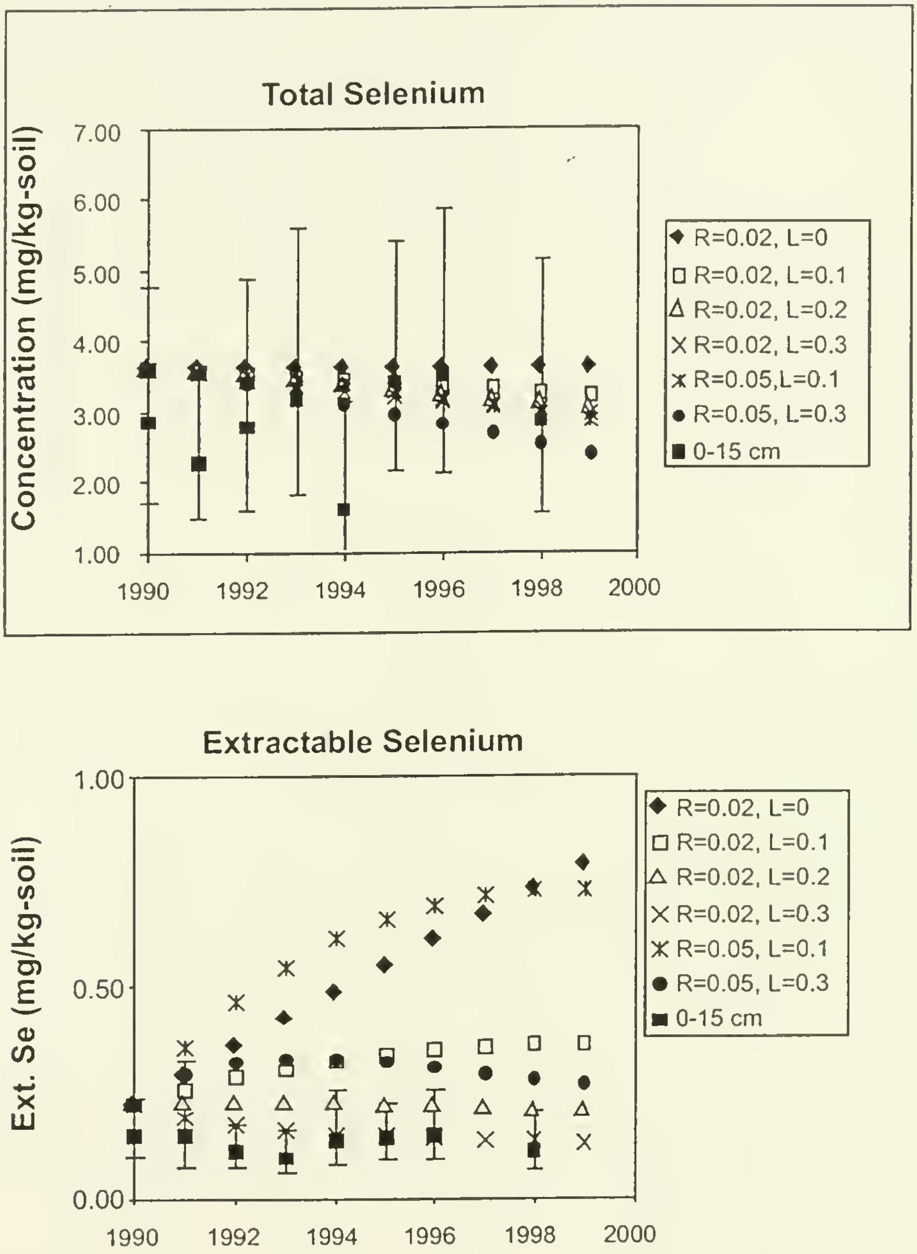


Figure 3-9a,b. Calculated time trends for a range of re-oxidation and leaching rates, compared to data collected from the Grassland habitat (0-15 cm).

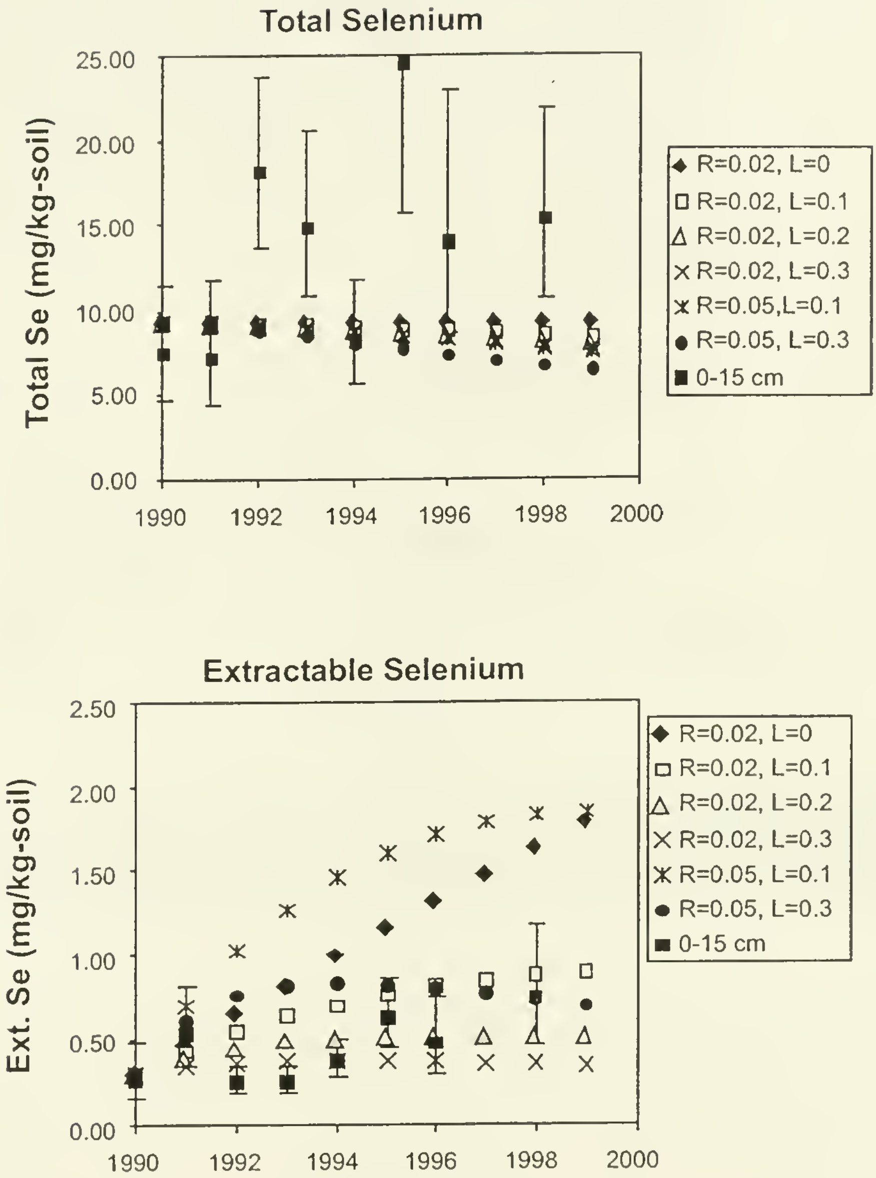


Figure 3-9c,d. Calculated time trends for a range of re-oxidation and leaching rates, compared to data collected from the Open habitat (0-15 cm).

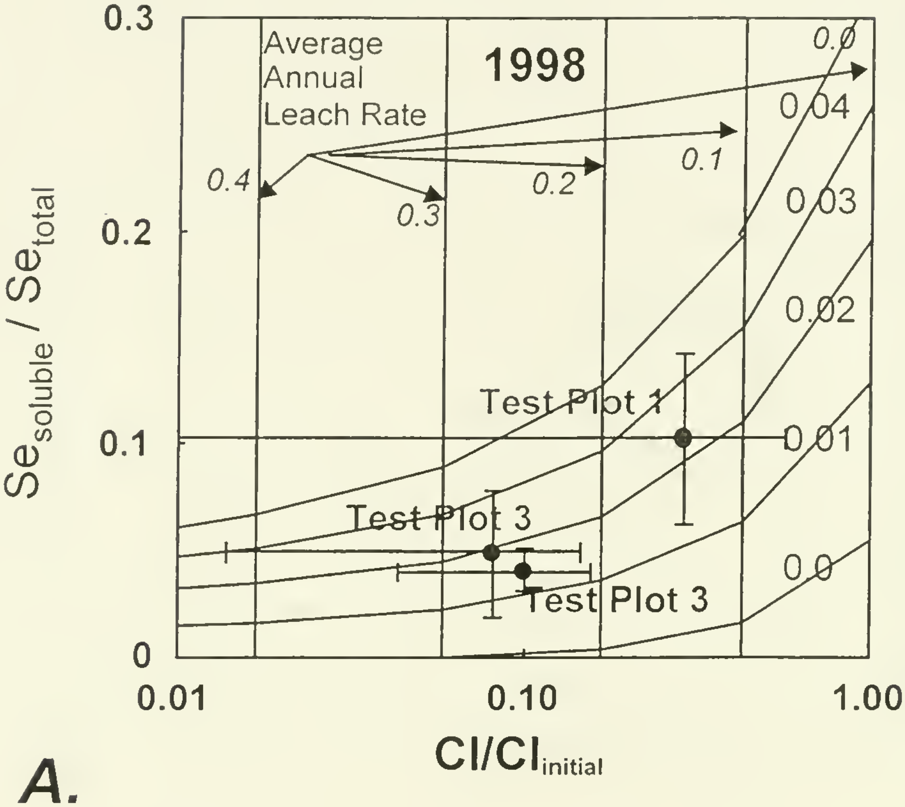


Figure 3-10. Analysis of re-oxidation rates from the SLD experimental plot in Pond 7 (a, b) and from the Pond 2 Volatilization Study site (c, d, e).

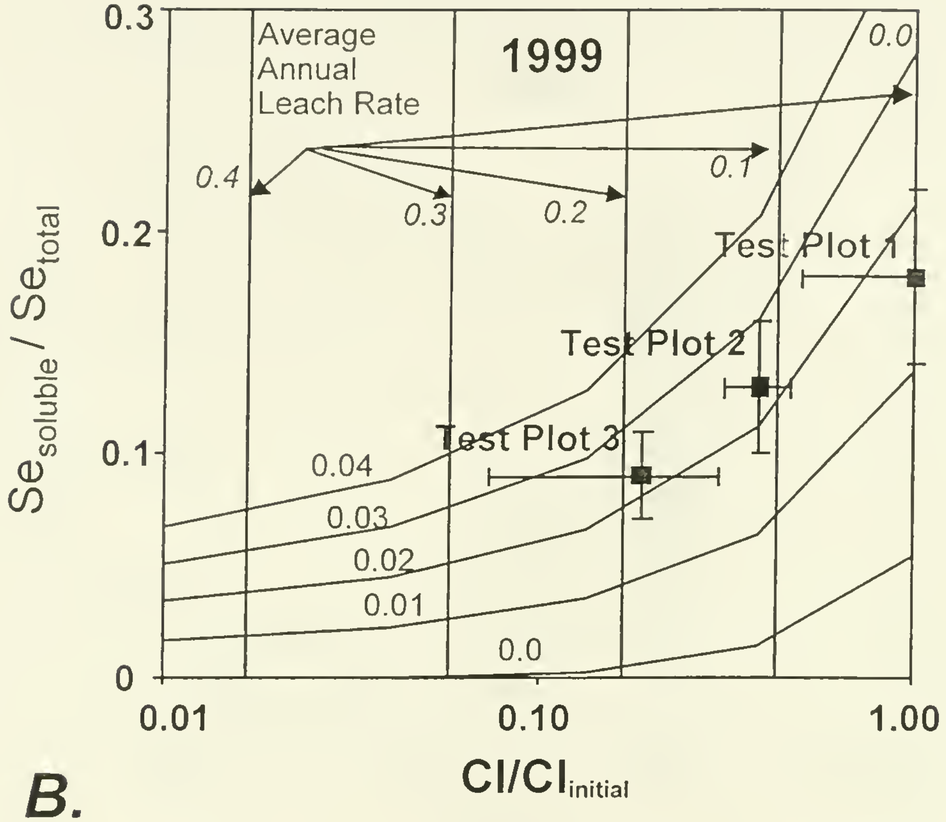


Figure 3-10. Analysis of re-oxidation rates from the SLD experimental plot in Pond 7 (a, b) and from the Pond 2 Volatilization Study site (c, d, e).

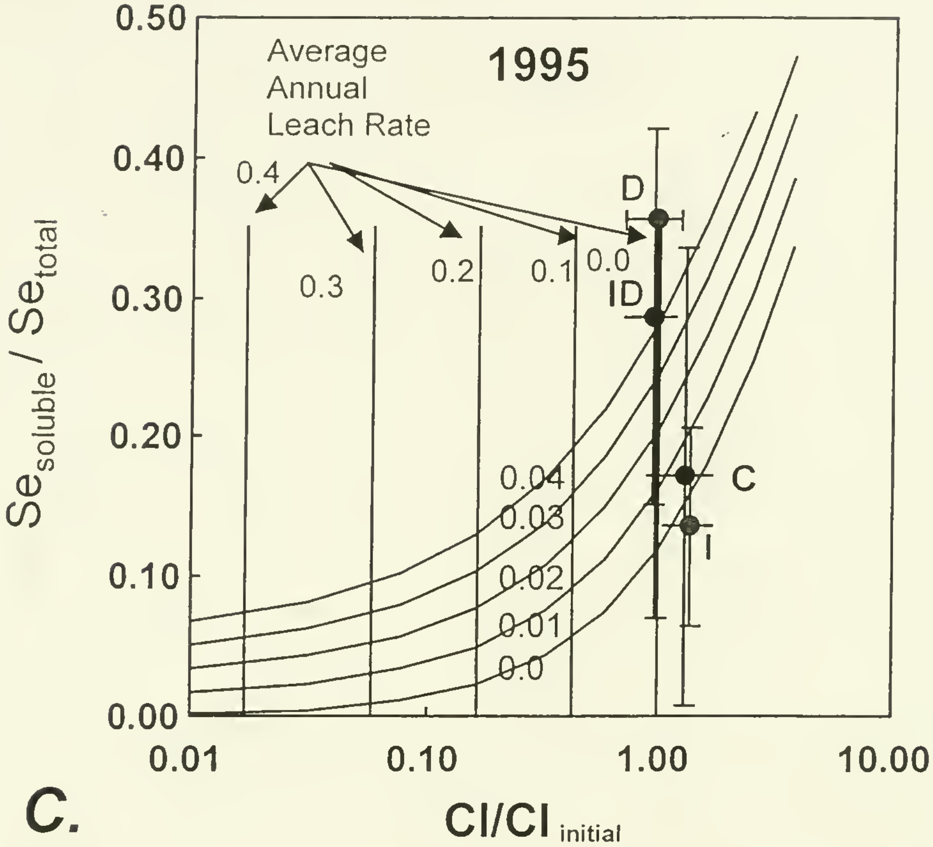


Figure 3-10. Analysis of re-oxidation rates from the SLD experimental plot in Pond 7 (a, b) and from the Pond 2 Volatilization Study site (c, d, e).

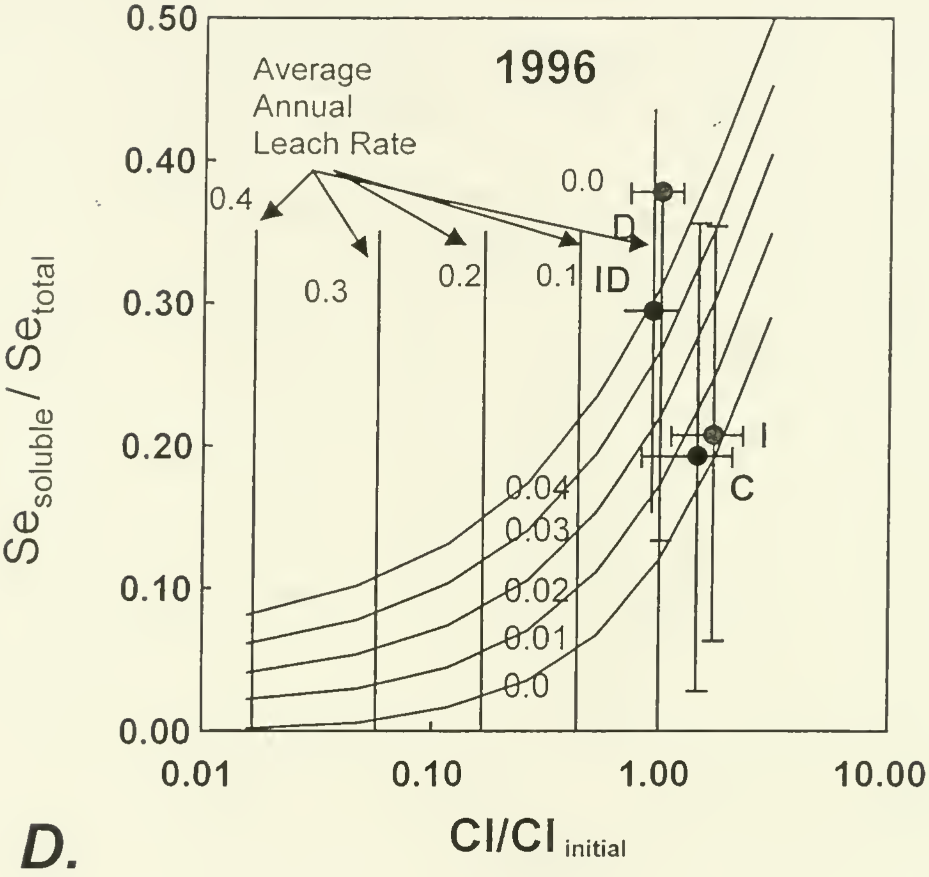


Figure 3-10. Analysis of re-oxidation rates from the SLD experimental plot in Pond 7 (a, b) and from the Pond 2 Volatilization Study site (c, d, e).

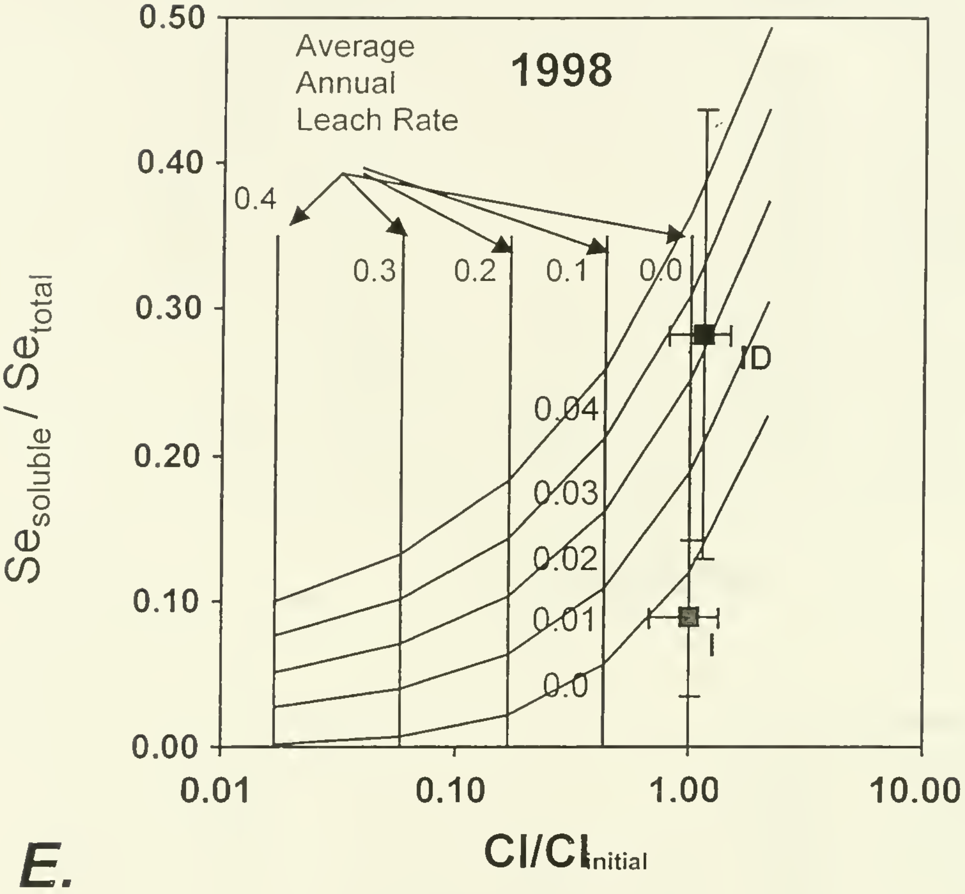
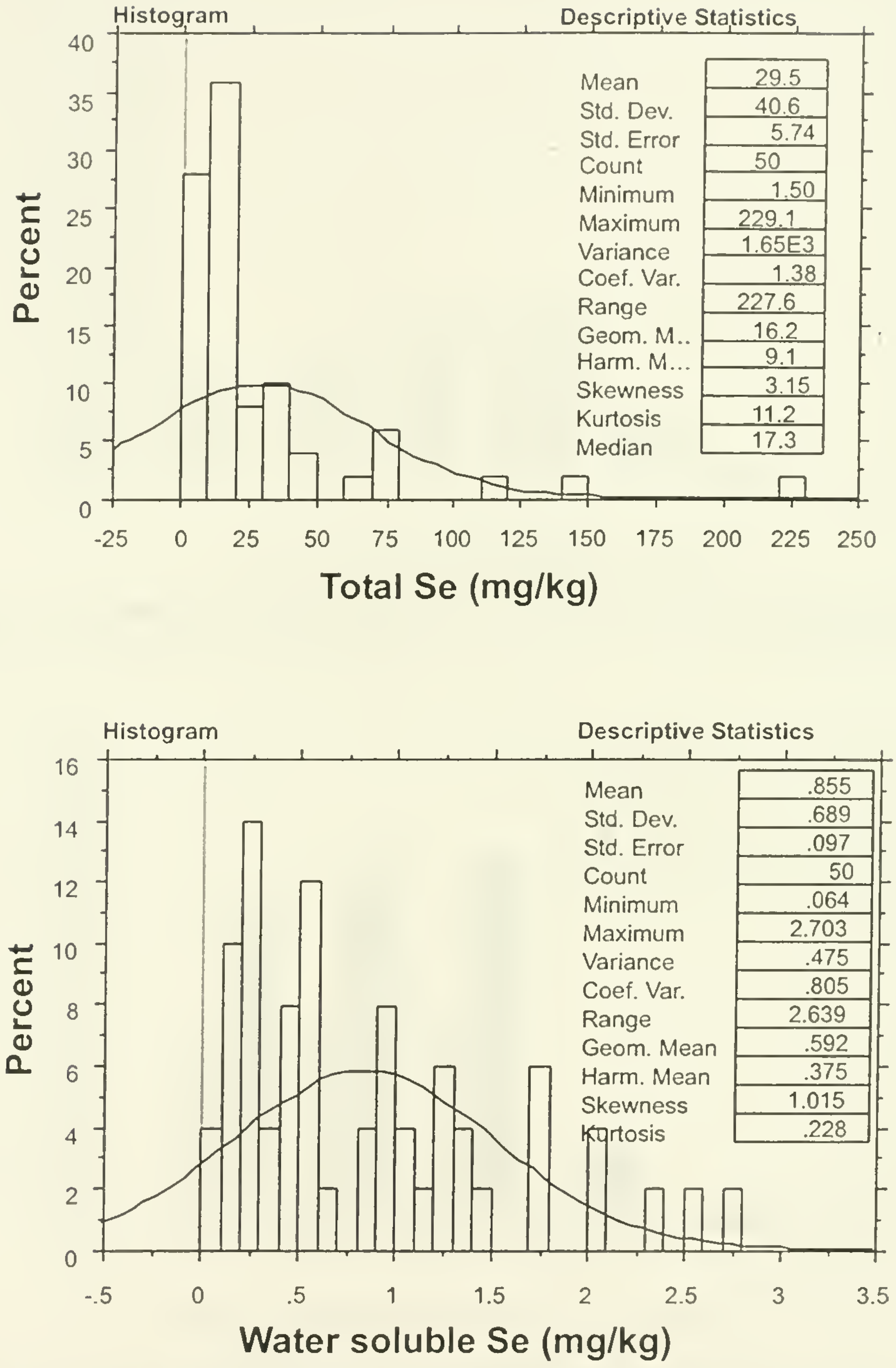


Figure 3-10. Analysis of re-oxidation rates from the SLD experimental plot in Pond 7 (a, b) and from the Pond 2 Volatilization Study site (c, d, e).



Mean	29.5
Std. Dev.	40.6
Std. Error	5.74
Count	50
Minimum	1.50
Maximum	229.1
Variance	1.65E3
Coef. Var.	1.38
Range	227.6
Geom. M..	16.2
Harm. M...	9.1
Skewness	3.15
Kurtosis	11.2
Median	17.3

Mean	.855
Std. Dev.	.689
Std. Error	.097
Count	50
Minimum	.064
Maximum	2.703
Variance	.475
Coef. Var.	.805
Range	2.639
Geom. Mean	.592
Harm. Mean	.375
Skewness	1.015
Kurtosis	.228

Figure 3-11. Histograms showing the distribution of total and water-soluble selenium in shallow (0-15 cm) soils in Open habitat sites in Trisection 1. The curve defines a hypothetical normal distribution around the given mean.

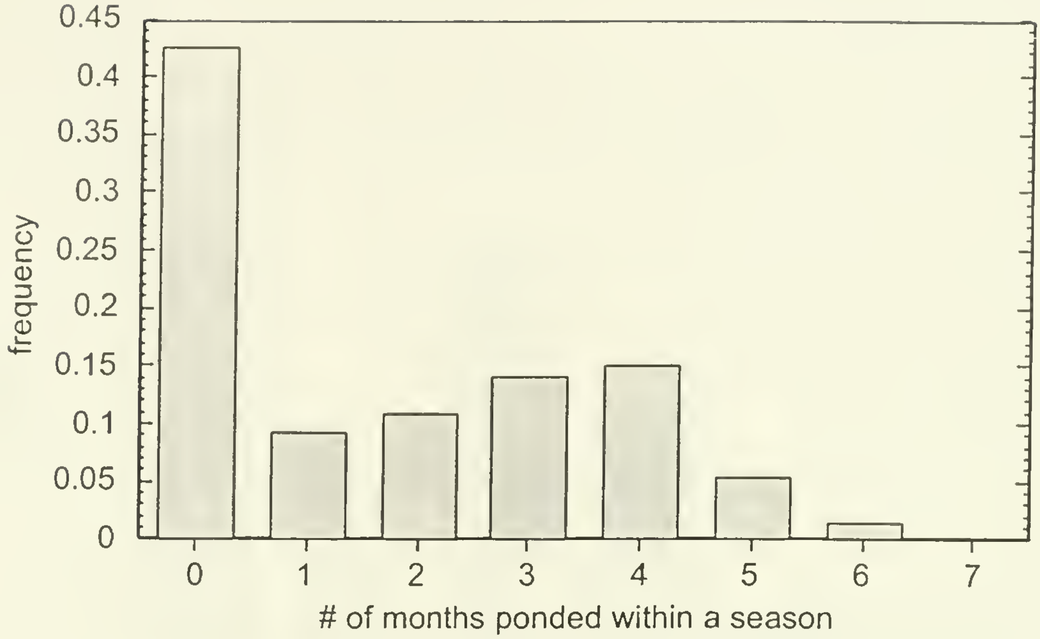


Figure 3-12. Estimated probability of ponding, and estimated probability of pool duration.

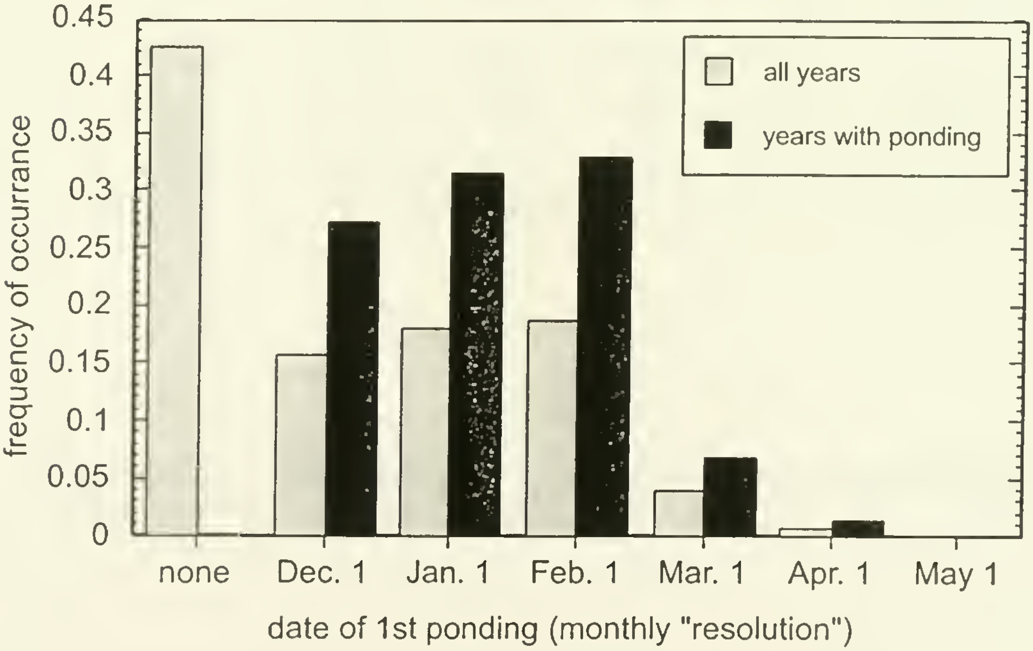


Figure 3-13. Estimated probabilities for months in which initial ephemeral pool formation occurs (for years in which ponding occurs).

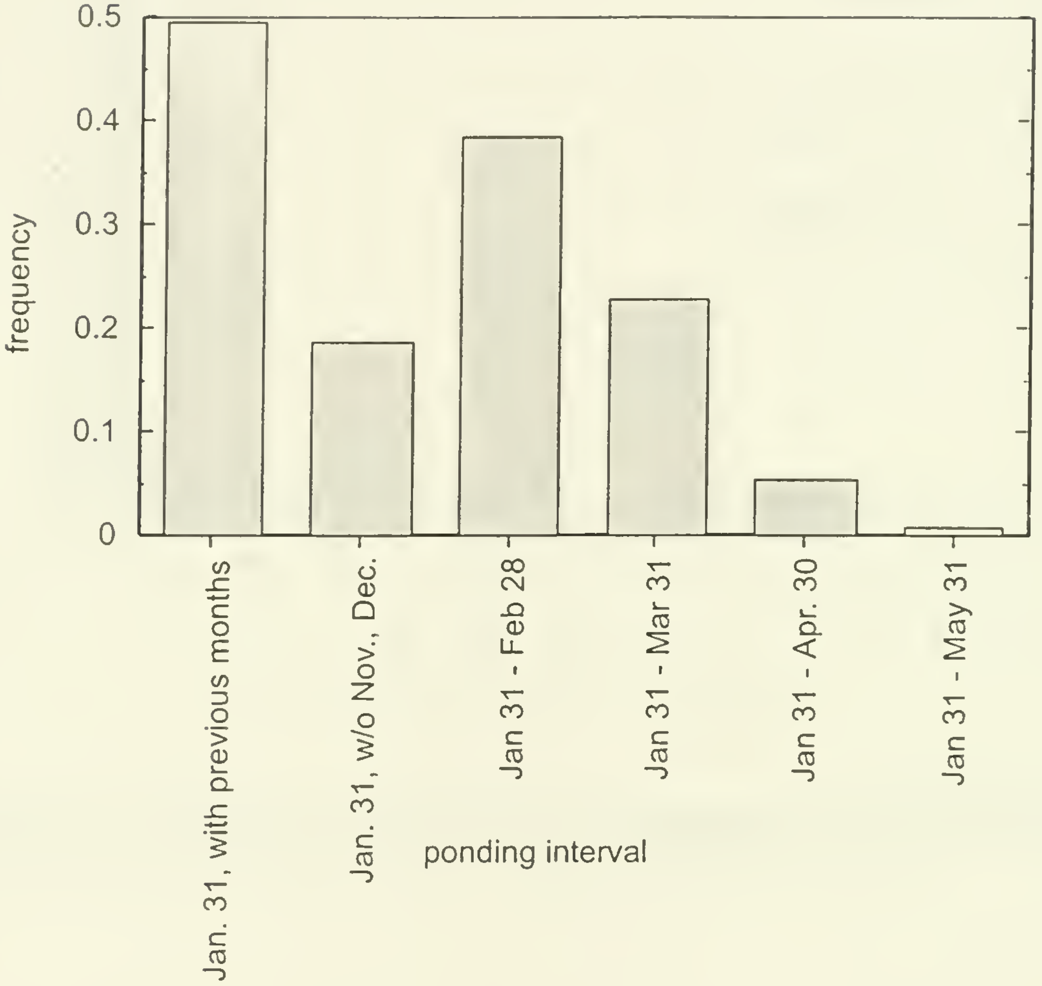


Figure 3-14. Frequency in which ponding is predicted to occur during January through May.

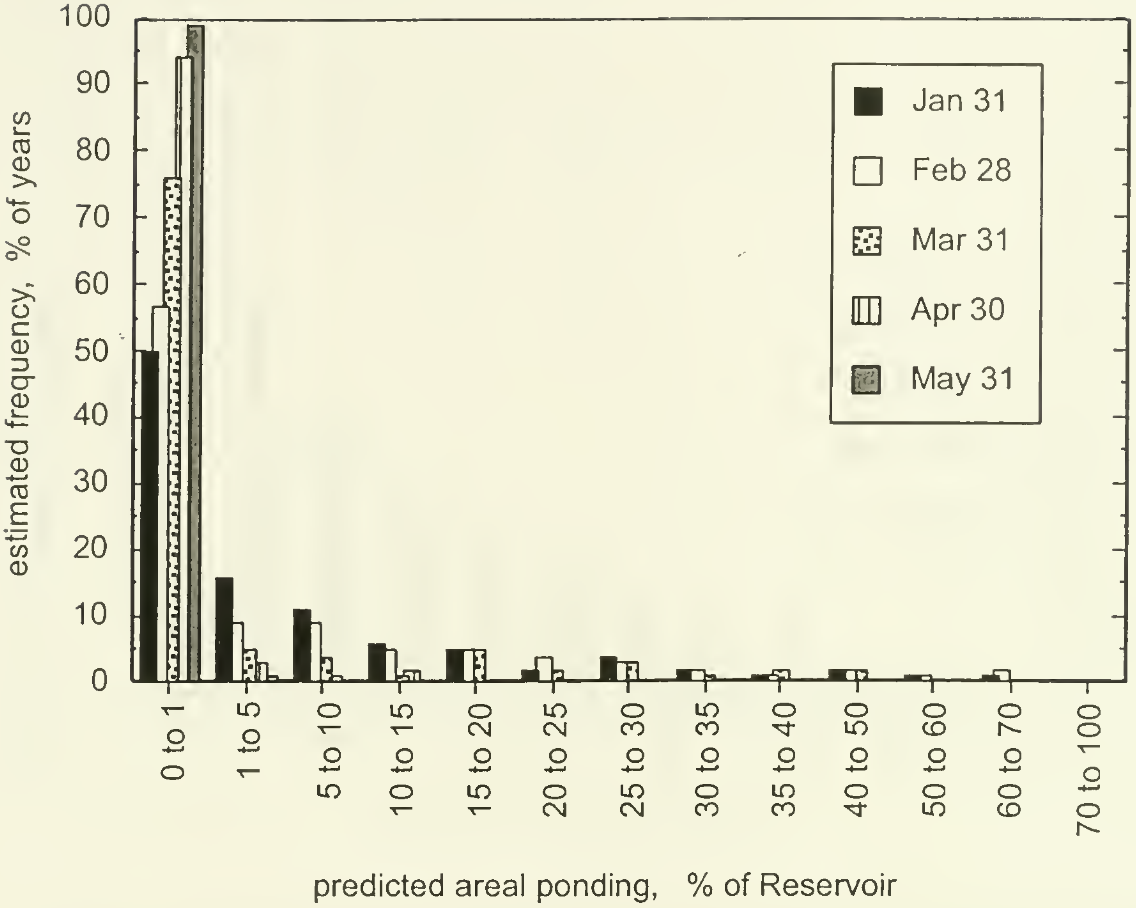


Figure 3-15. Estimated probability for ephemeral pool areal coverage at the end of January, February, March, April, and May.

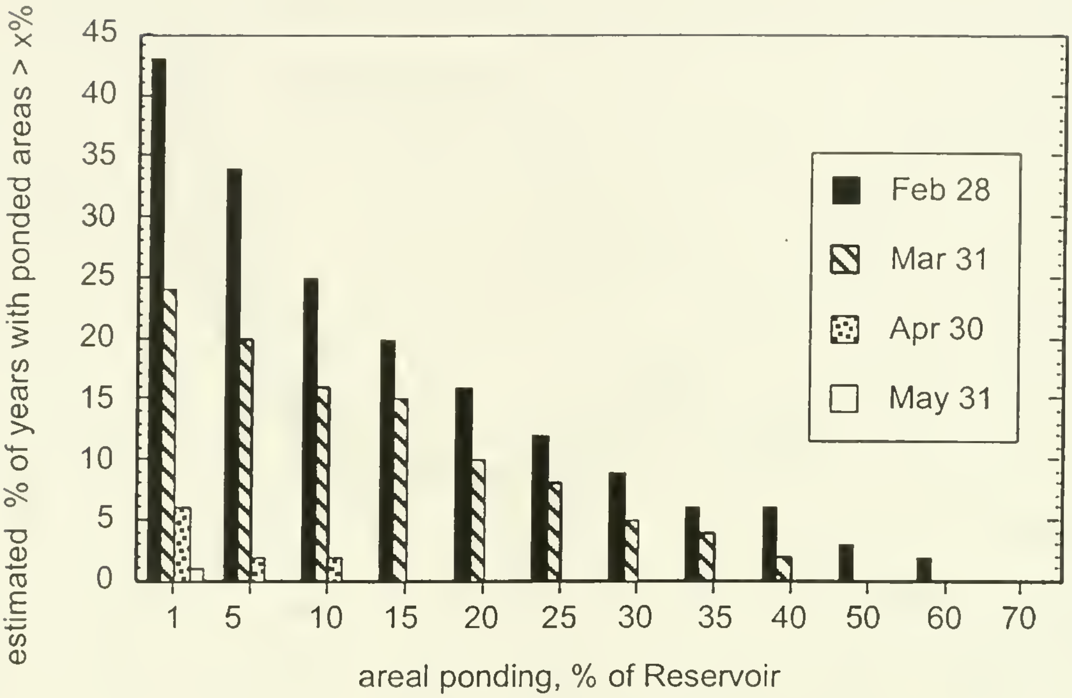


Figure 3-16. Estimated probability for ephemeral pool areal coverage exceeding x% at the end of February, March, April, and May.

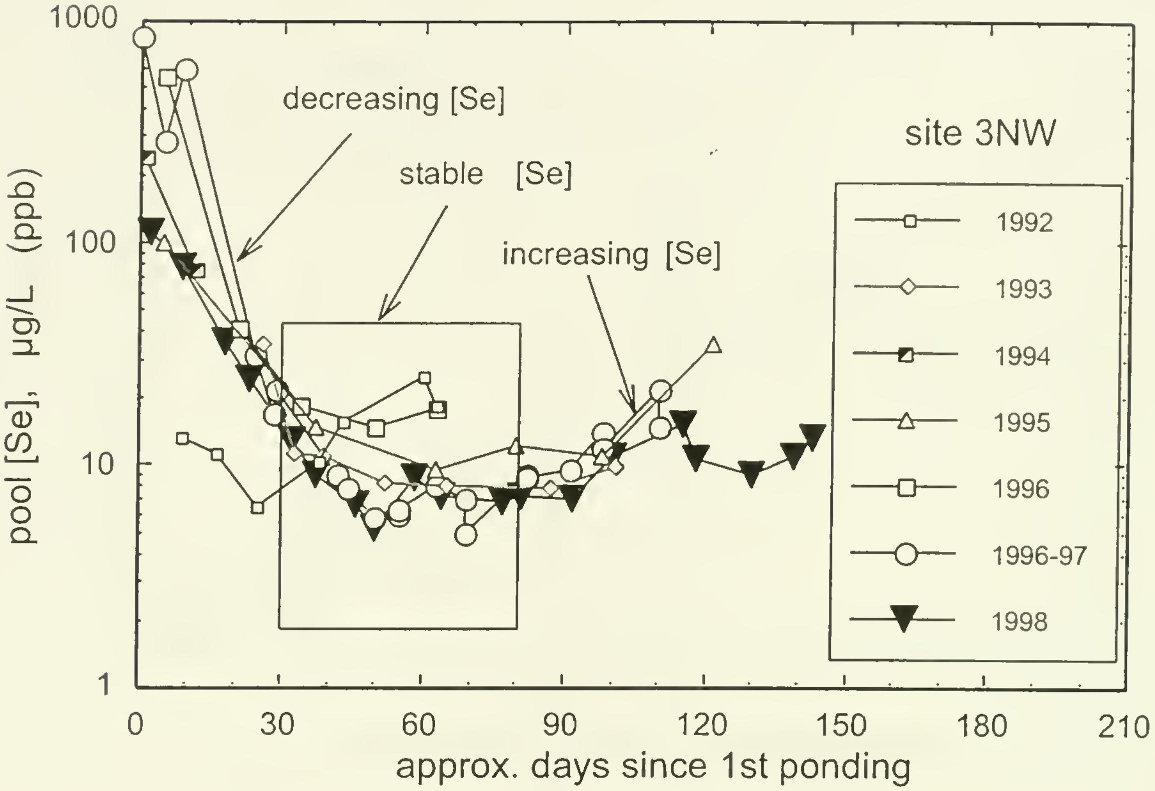


Figure 3-17. Typical ephemeral pool selenium concentration pattern following initial ponding, site 3NW.

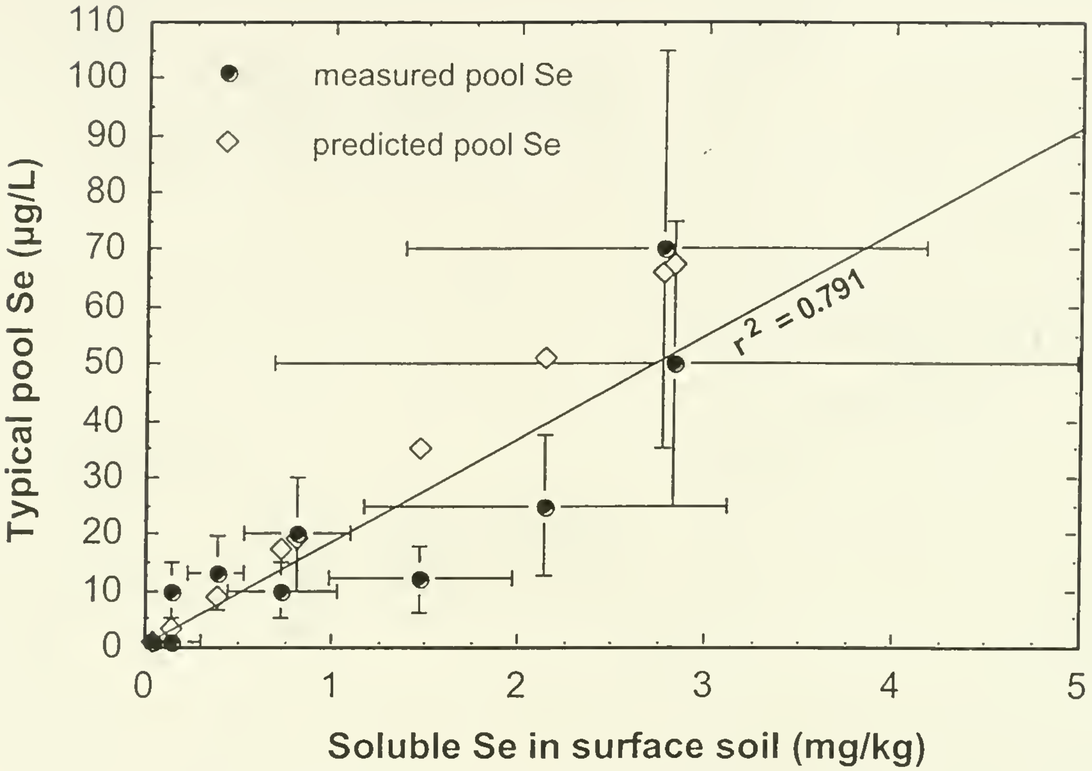
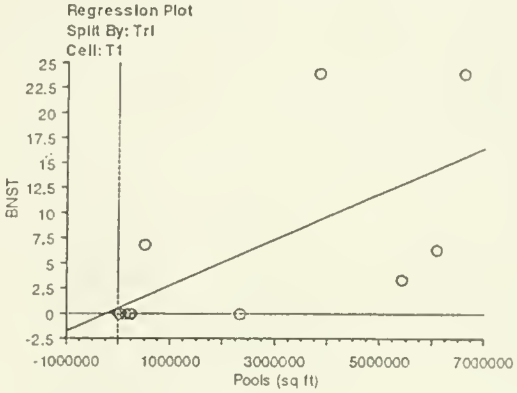


Figure 3-18. Measured and predicted ephemeral pool selenium based on soluble selenium in surface soil.

ANOVA Table
BNST vs. Pools (sq ft)
Split By: Tri
Cell: T1

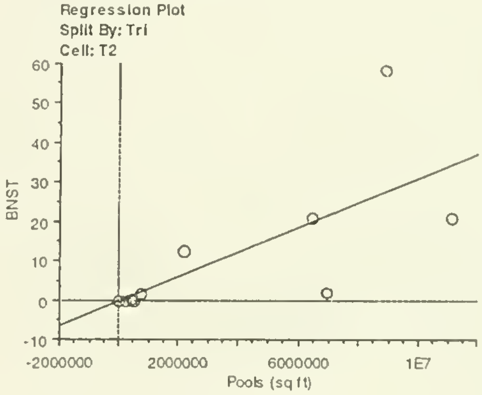
	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	398.139	398.139	7.890	.0185
Residual	10	504.601	50.460		
Total	11	902.739			



Y = .513 + 2.286E-6 * X; R^2 = .441

ANOVA Table
BNST vs. Pools (sq ft)
Split By: Tri
Cell: T2

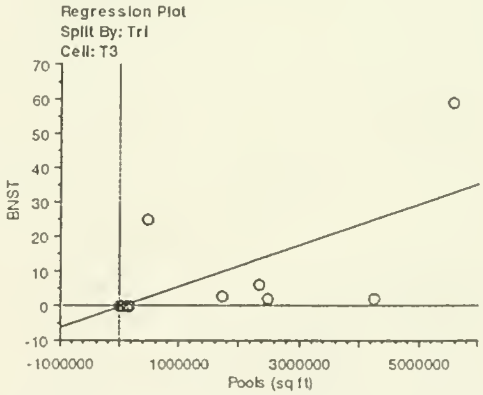
	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	1761.786	1761.786	11.161	.0075
Residual	10	1578.482	157.848		
Total	11	3340.267			



Y = -.076 + 3.13E-6 * X; R^2 = .527

ANOVA Table
BNST vs. Pools (sq ft)
Split By: Tri
Cell: T3

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	1	1403.334	1403.334	7.043	.0242
Residual	10	1992.614	199.261		
Total	11	3395.948			



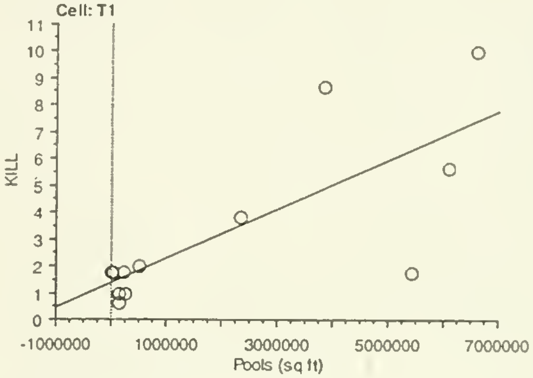
Y = -.442 + 5.983E-6 * X; R^2 = .413

Figure 3-19. Black-necked stilt daily use as a function of ponded area by trisection

ANOVA Table
KILL vs. Pools (sq ft)
Split By: Tri
Cell: T1

	Regression	Residual	Total
DF	1	10	11
Sum of Squares	64.113	45.169	109.282
Mean Square	64.113	4.517	
F-Value	14.194		
P-Value	.0037		

Regression Plot
Split By: Tri
Cell: T1

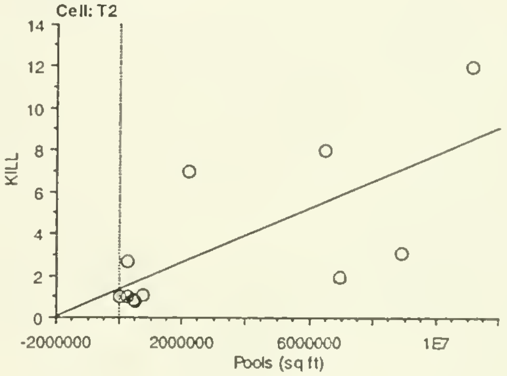


Y = 1.366 + 9.173E-7 * X; R^2 = .587

ANOVA Table
KILL vs. Pools (sq ft)
Split By: Tri
Cell: T2

	Regression	Residual	Total
DF	1	10	11
Sum of Squares	76.004	70.286	146.289
Mean Square	76.004	7.029	
F-Value	10.814		
P-Value	.0082		

Regression Plot
Split By: Tri
Cell: T2

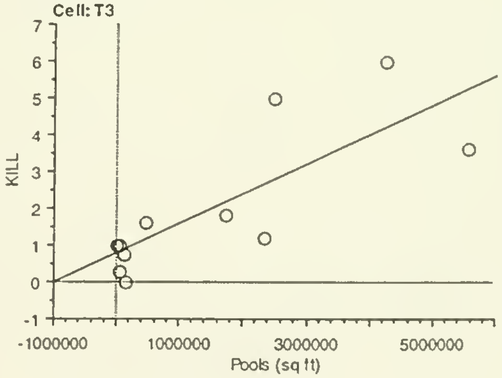


Y = 1.341 + 6.502E-7 * X; R^2 = .52

ANOVA Table
KILL vs. Pools (sq ft)
Split By: Tri
Cell: T3

	Regression	Residual	Total
DF	1	10	11
Sum of Squares	25.453	14.492	39.945
Mean Square	25.453	1.449	
F-Value	17.564		
P-Value	.0019		

Regression Plot
Split By: Tri
Cell: T3

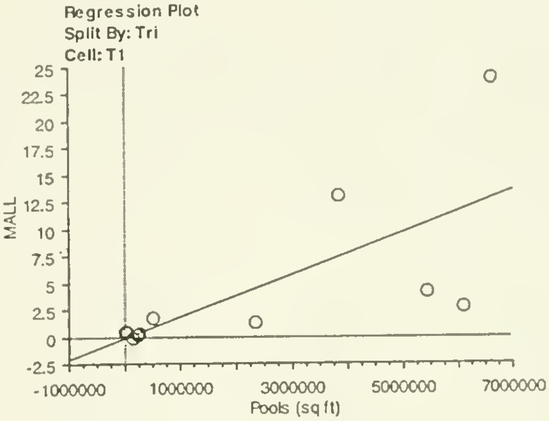


Y = .792 + 8.058E-7 * X; R^2 = .637

Figure 3-20. Killdeer daily use as a function of ponded area by trisection.

ANOVA Table
MALL vs. Pools (sq ft)
Split By: Tri
Cell: T1

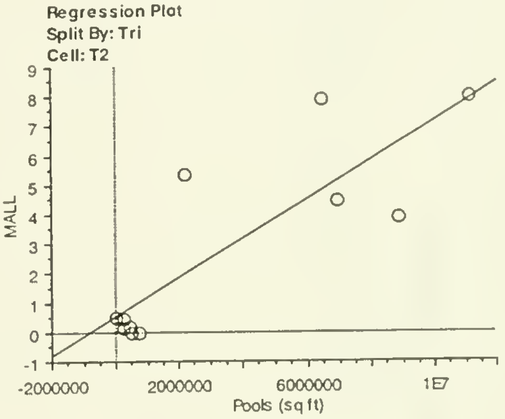
	Regression	Residual	Total
DF	1	10	11
Sum of Squares	291.930	287.887	579.817
Mean Square	291.930	28.789	
F-Value	10.140		
P-Value	.0097		


Regression Plot
Split By: Tri
Cell: T1

Y = -.097 + 1.957E-6 * X; R^2 = .503

ANOVA Table
MALL vs. Pools (sq ft)
Split By: Tri
Cell: T2

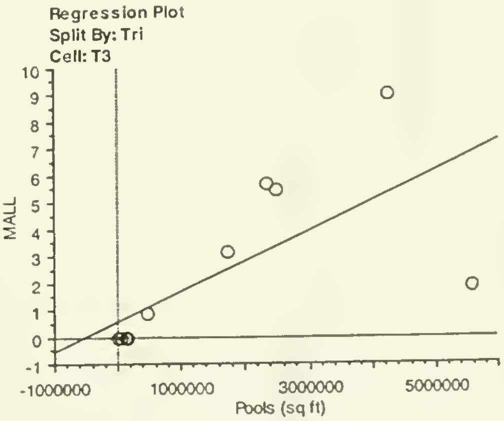
	Regression	Residual	Total
DF	1	10	11
Sum of Squares	78.543	30.068	108.611
Mean Square	78.543	3.007	
F-Value	26.122		
P-Value	.0005		


Regression Plot
Split By: Tri
Cell: T2

Y = .54 + 6.609E-7 * X; R^2 = .723

ANOVA Table
MALL vs. Pools (sq ft)
Split By: Tri
Cell: T3

	Regression	Residual	Total
DF	1	10	11
Sum of Squares	49.563	51.636	101.200
Mean Square	49.563	5.164	
F-Value	9.598		
P-Value	.0113		


Regression Plot
Split By: Tri
Cell: T3

Y = .57 + 1.124E-6 * X; R^2 = .49

Figure 3-21. Mallard daily use as a function of ponded area by trisection.

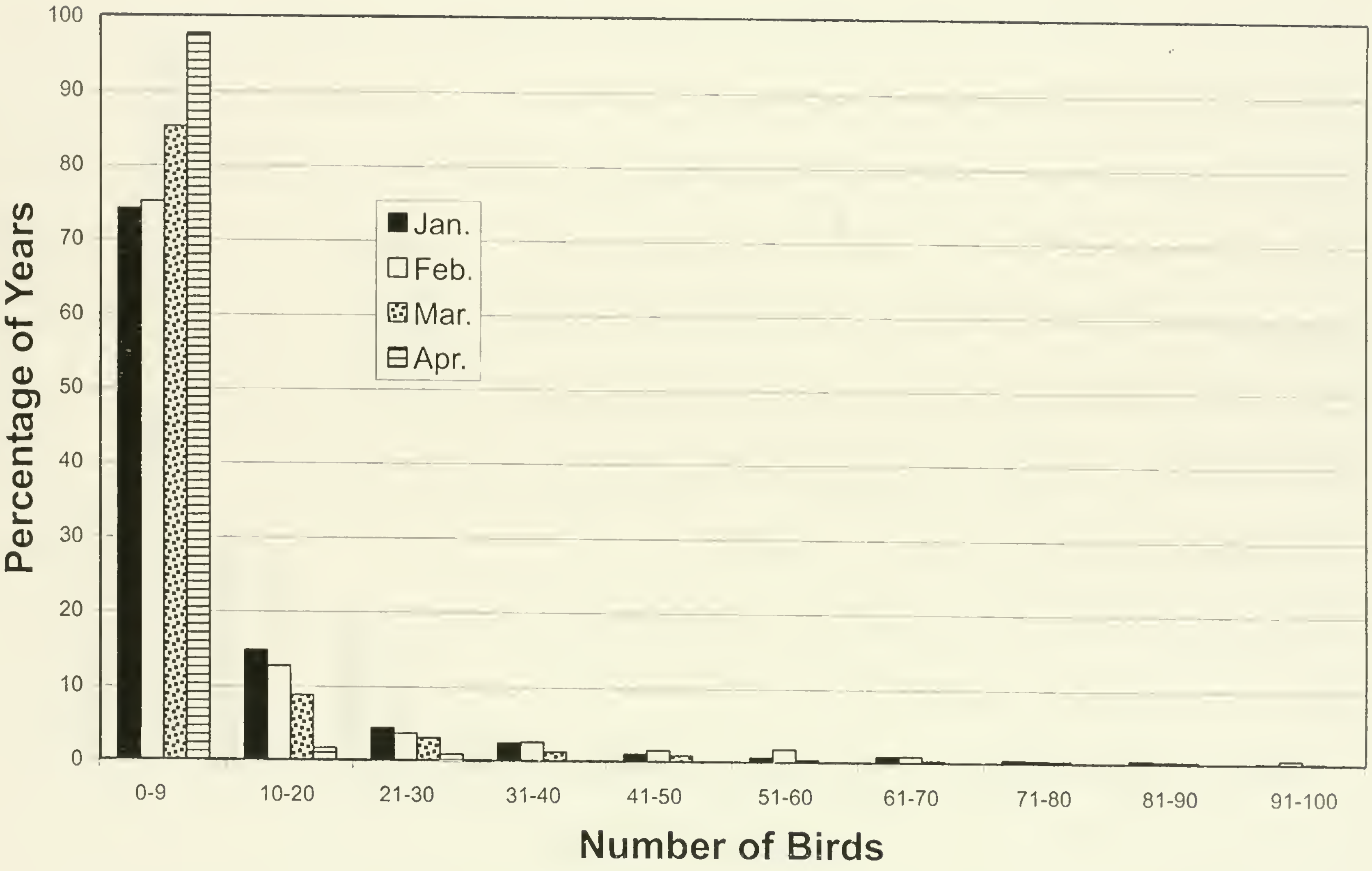


Figure 4-1. Black-Necked Stilt daily use estimates.

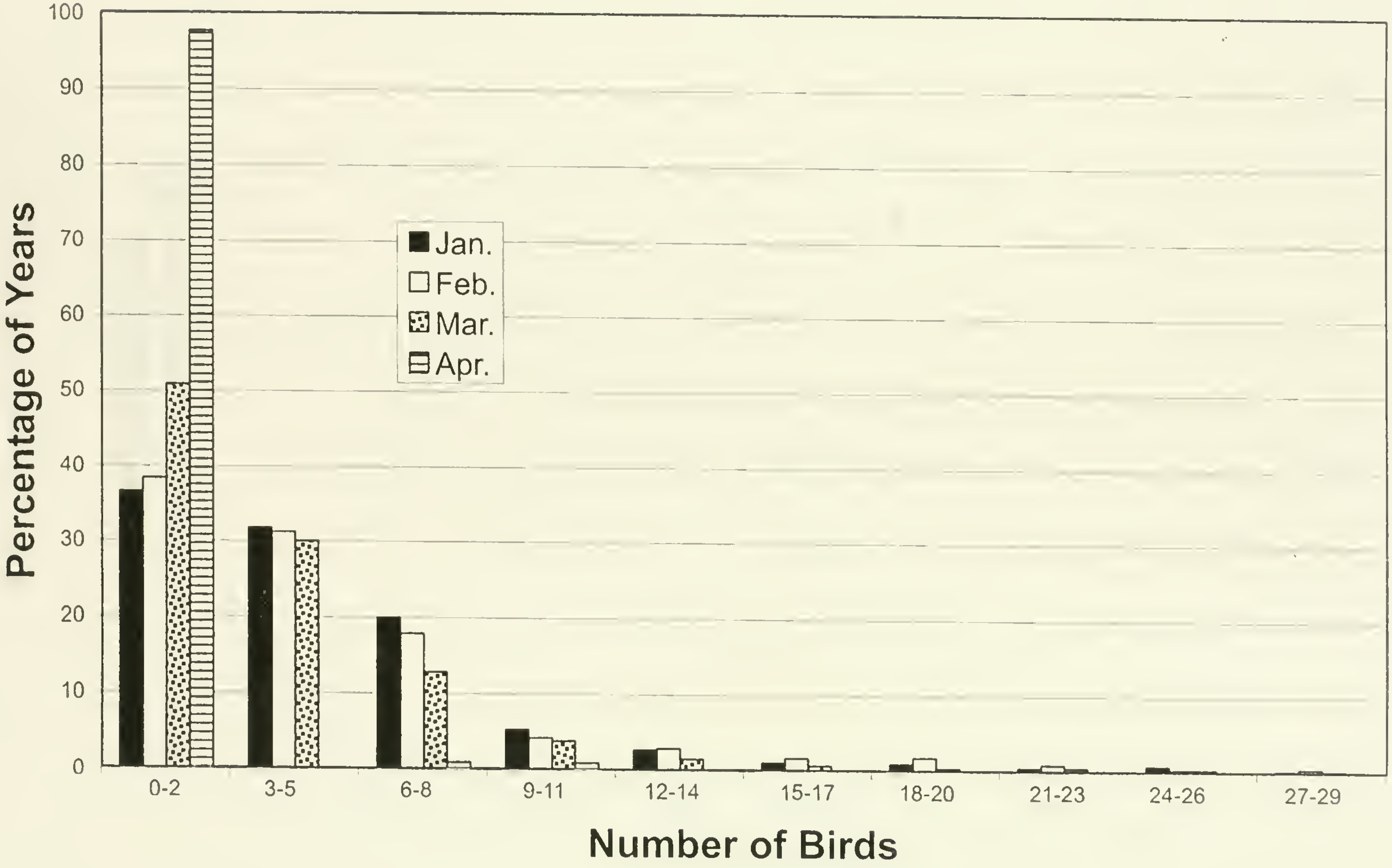


Figure 4-2. Killdeer daily use estimates.

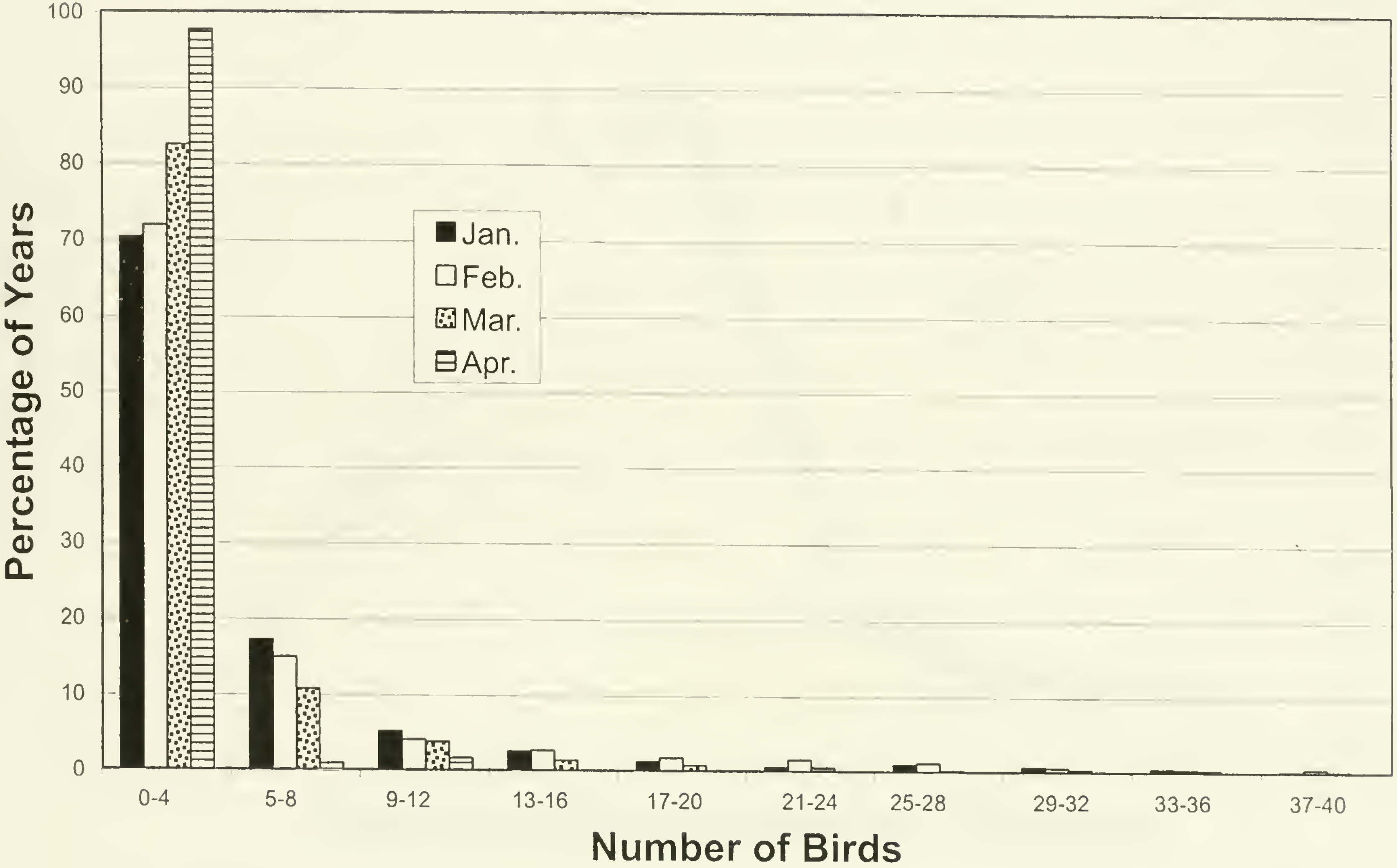


Figure 4-3. Mallard daily use estimates.

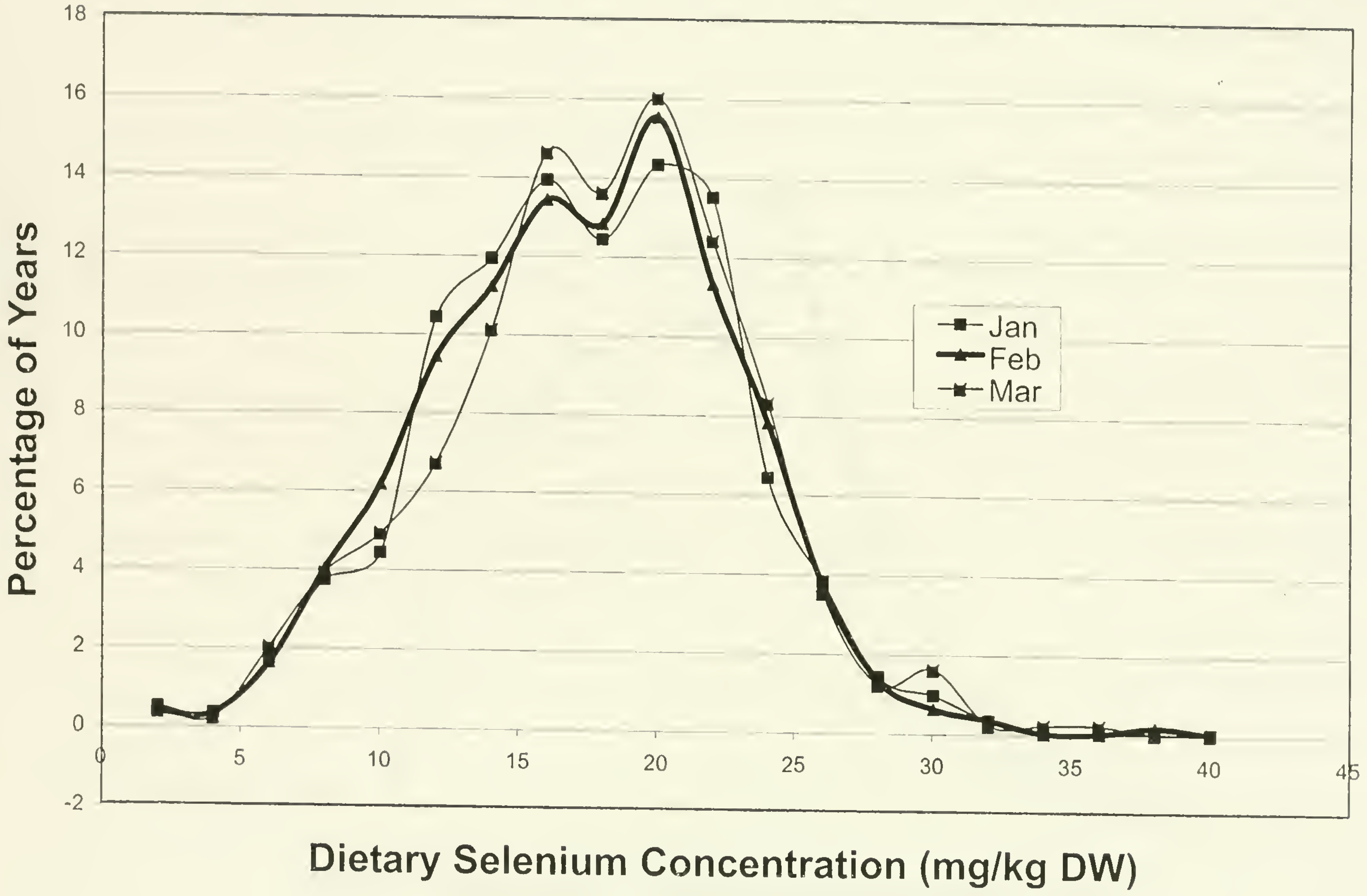


Figure 4-4. Black-Necked Stilt dietary selenium

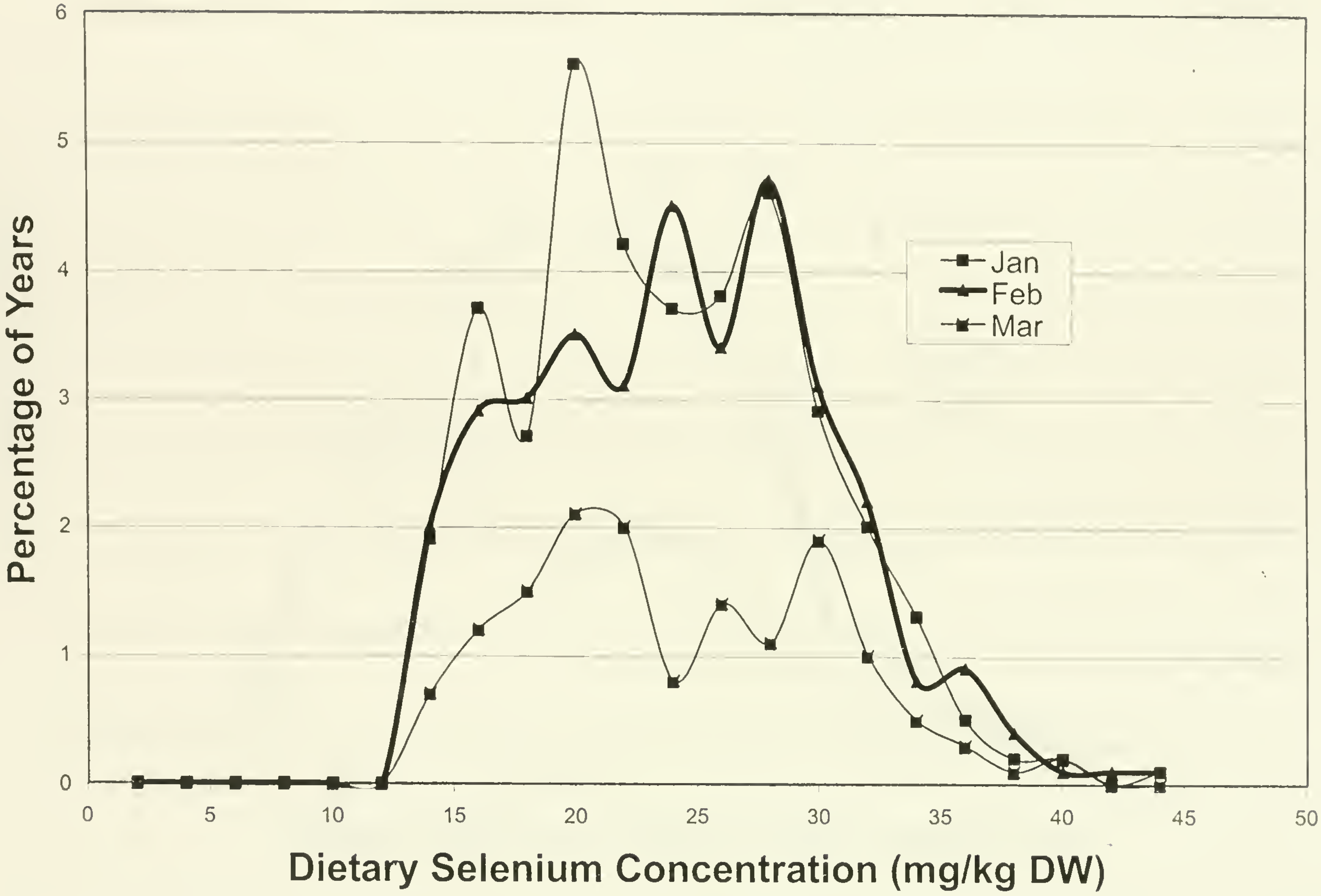


Figure 4-5. Killdeer aquatic dietary selenium

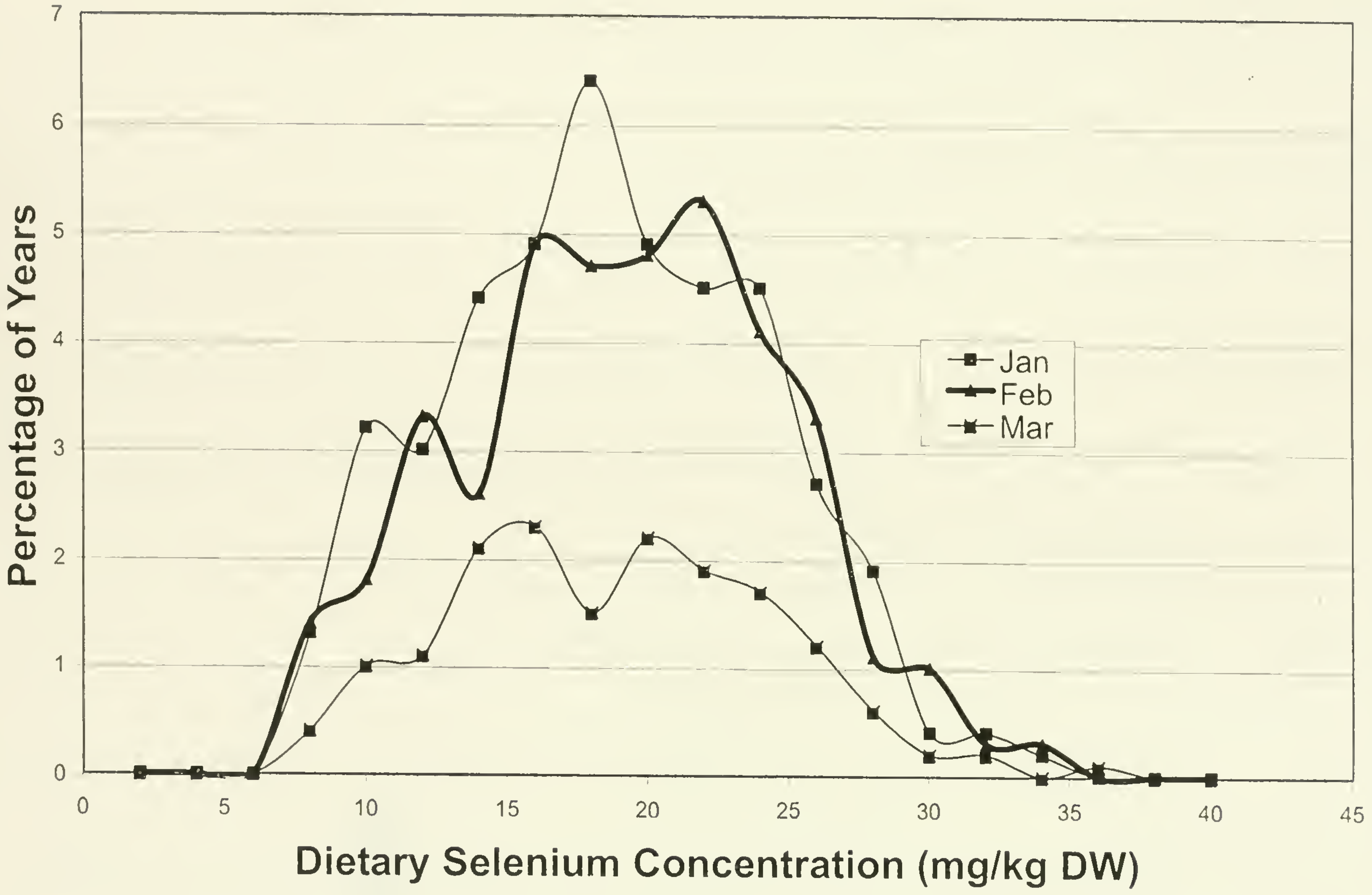


Figure 4-6. Mallard aquatic dietary selenium

Appendix A

APPENDIX A

Groundwater Elevation and Groundwater Quality

Groundwater Elevation

The ecological risk assessment requires the understanding of future climatic and hydrologic conditions at Kesterson Reservoir. Rainfall records presented in Appendix B indicate cyclic climatic changes but no long-term trends. However, the elevation of the groundwater table depends on a number of other factors, including regional and local groundwater use, and the flooding of neighboring areas for wildlife habitat. Historical records in the Kesterson area allow for the study of groundwater fluctuations as influenced by water use and climate over the last few decades, as well as of more local effects due to flooding of the Freitas Unit to the east of the Reservoir over the last 5 years.

Numerous shallow groundwater wells were operated from approximately 1970 until 1995 in and around Kesterson Reservoir. Most of those wells are no longer used. A newer generation of wells installed in the mid-1980s is currently monitored. We have examined records from both sets of wells and have been able to combine them to obtain a record from 1970 through the present. An example of such a combined record is shown in Fig. A-1, where data from wells D10-W1 and KR7 are composited. Well D10-W1 is located at the junction of Pond 8, Pond 10 and the western boundary berm road. Well KR7 is just west of D10-W1. This combined record shows the effects of extreme hydrologic events, specifically the El Niño winters in 1983-84 and 1997-98, and the drought period in the late 1980s to early 1990s. The peak in the D10-W1 record in the winter of 1995 is an outlier and is one of only two points where a discrepancy between the two records exists. The overall long-term record for these two wells, which is representative of many others in the area, does not show any consistent trends of either rising or falling water table.

The effects of the flooding of the Freitas Unit should be apparent in groundwater records from wells on the eastern boundary of the Reservoir. Well D2-W2 is located near the corners of Ponds 2, 3, and 4. It was installed in 1982 and therefore the data set captures the effects of the progressive draining of the Reservoir in the mid 1980s (Figure A-2). Subsequent fluctuations are due to seasonal changes in the regional groundwater table. The amplitude of these fluctuations is about ±3 ft around an annual mean elevation. A comparison of water table fluctuations from the late 1980s through 1995, with the patterns observed in 1999 and 2000, reveals the effects of the progressive flooding of the Freitas Unit, which was effectively completed in 1998. The wintertime high elevations do not differ between those two periods, when the hydrology is controlled largely by regional groundwater table rise. However, the summertime low levels are approximately 1 ft higher in 1999/2000 than in most, but not all, of the earlier years. Similar patterns are observed in Well LBL-7, which is located approximately 400 ft ENE of the southeast corner of Pond 7 (Figure A-3). These records lead us to believe that the effects of the Freitas Unit flooding on Kesterson Reservoir

groundwater levels are discernable but minor. Observations of very local ponding along the eastern boundary, primarily in Pond 5, suggest that small-scale topographic depressions will be most affected by the Freitas Unit flooding.

Groundwater Quality

Groundwater quality has been monitored at Kesterson Reservoir to measure the off-site movement of the groundwater plume. Boron is used as a conservative tracer for this plume because of its relatively high concentrations in the drainwater applied to Kesterson during its operation. Off-site groundwater selenium concentrations are generally below detection or in the 1 to 3 μg/L range. This is to be expected as most of the selenium was reduced and immobilized before reaching the groundwater and further chemically reduced below the water table. An examination of boron and selenium trends in monitoring wells over the last decade has shown the plume to be very slow-moving. These data are presented in Figures A-4 through A-7. Boron concentrations in wells LBL26, LBL27, LBL14, LBL8, and FR27 have fallen in a stable range between 1989 and the most recent measurements in February 2000. Data from LBL13, LBL7, and FR26 show fluctuations in boron values. These changes are likely the result of the operation of the Freitas Unit and do not show any net increases in boron. Decreases in boron in FR26 (Figure A-7) are indicative of a reversal of plume movement due to the hydraulic head imposed by the Freitas Unit wetlands. Wells D2-W2 and DH-9-2 (Figures A-8 and A-9) are within Kesterson Reservoir, in Ponds 2 and 9, respectively. Both boron and selenium in D2-W2 are fairly stable. Selenium concentrations in DH-9-2 have fluctuated due to the infiltration of rainwater through an unusually high-permeability soil. Although there is a time lag, selenium concentrations decrease following an infiltration event. The effect of the El Niño event in 1997 - 1998 is visible in the sample taken on 9/21/98. Observations over multiple years lend confidence to our understanding of the hydrogeochemistry of this local system. It is an isolated occurrence and the lateral spread of selenium in the groundwater is insignificant.

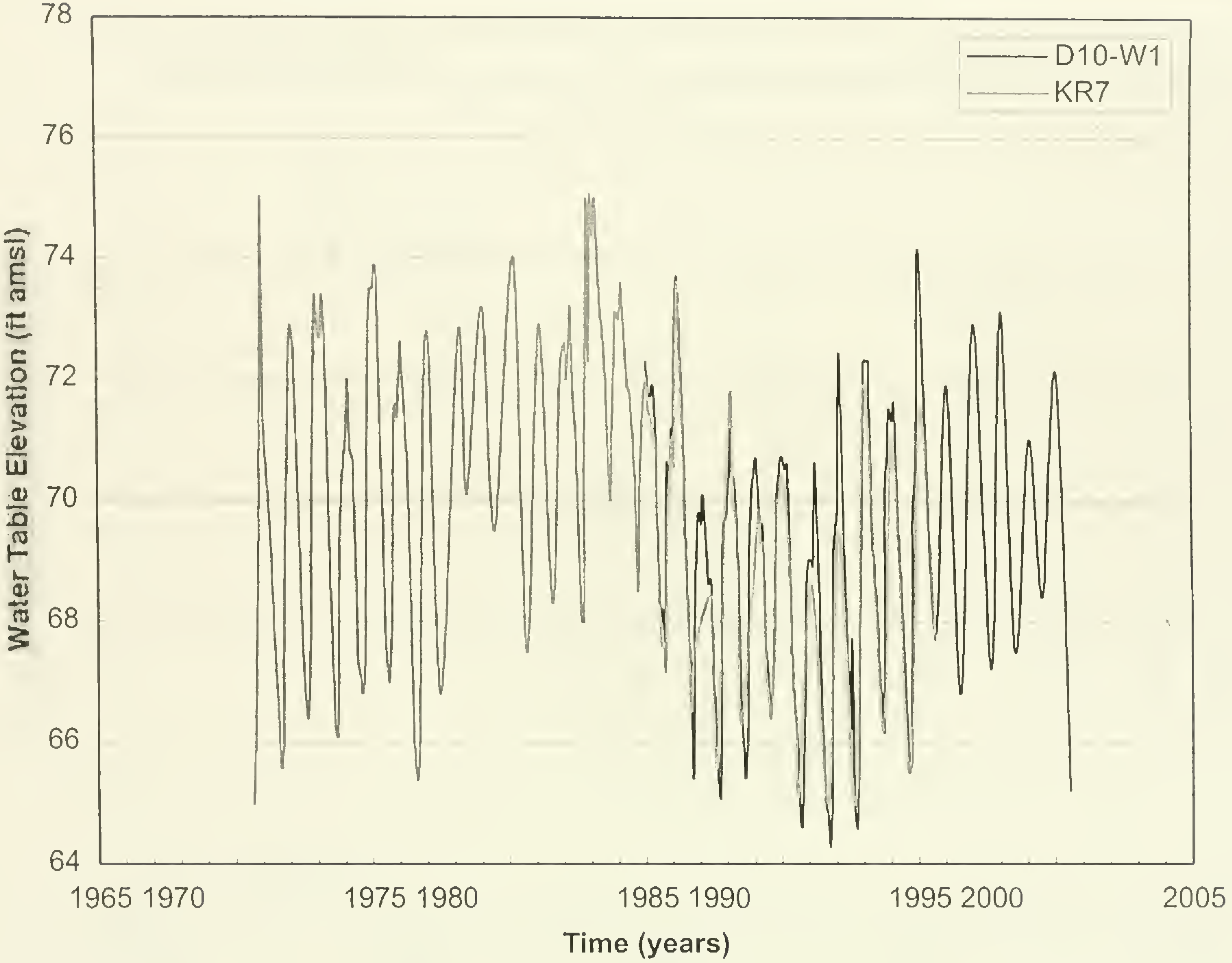


Figure A-1. Groundwater elevation in wells D10-W1 and KR7, 1970-present.

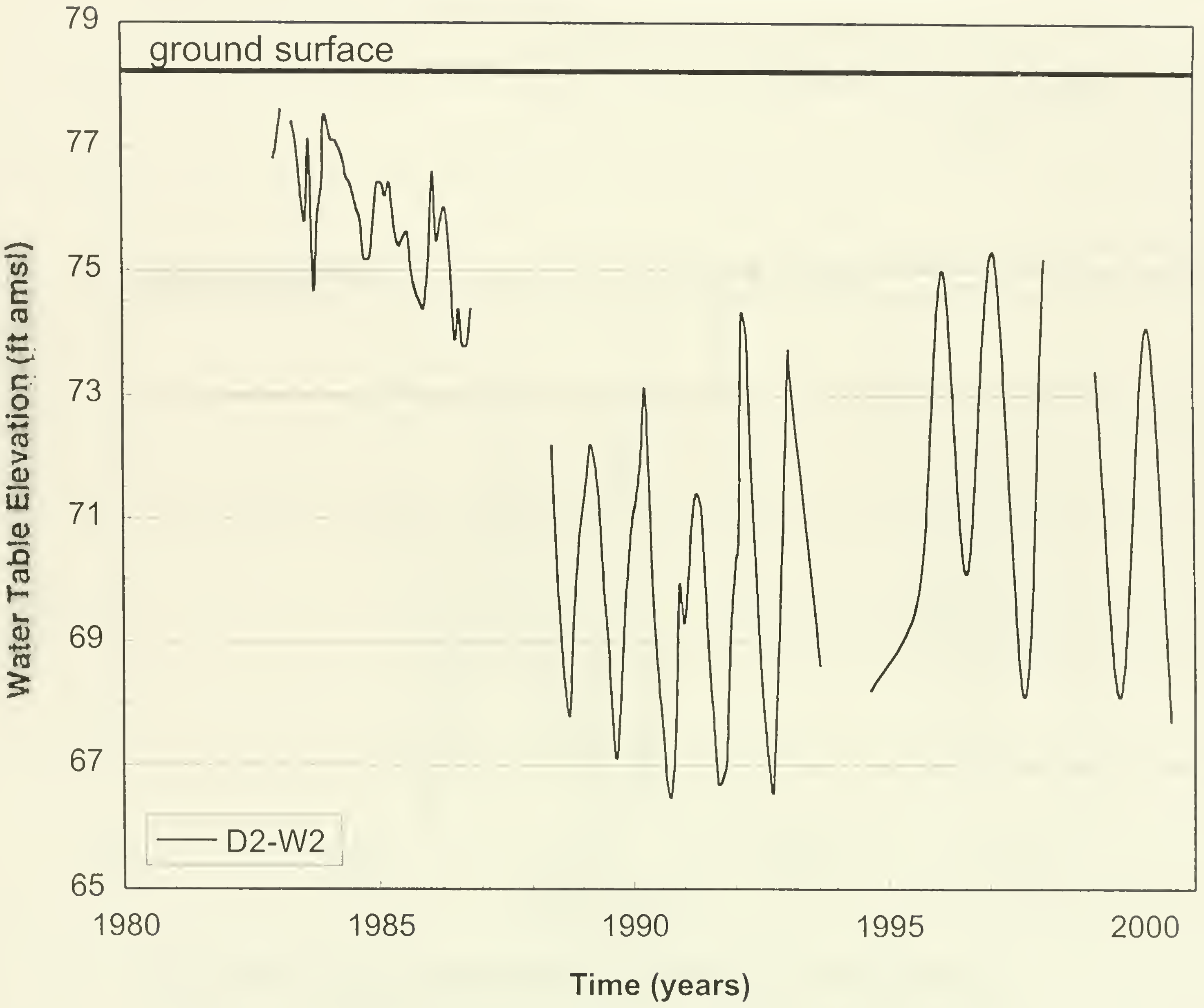


Figure A-2. Groundwater elevation in well D2-W2, 1982-present.

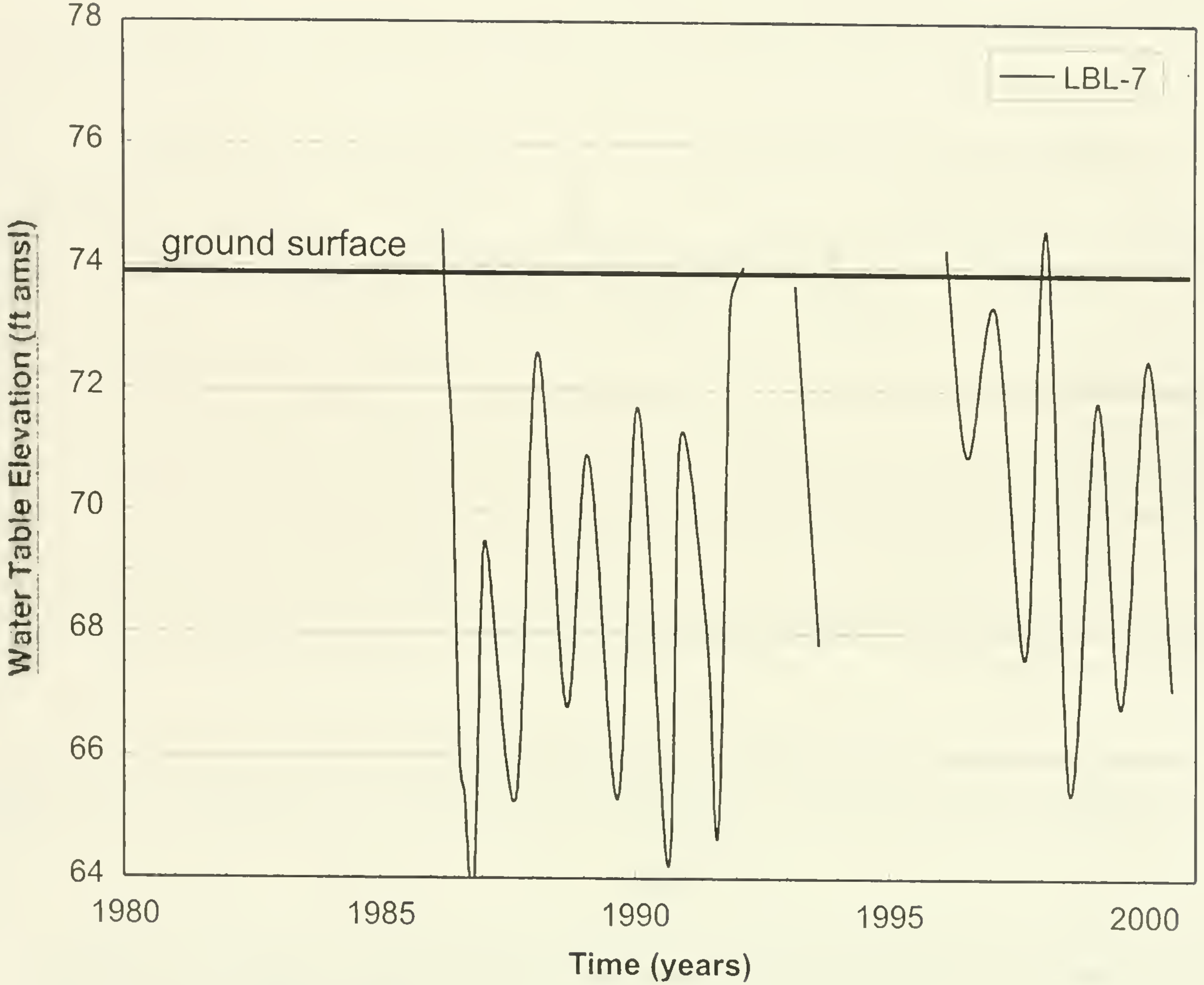


Figure A-3. Groundwater elevation in well LBL7, 1986-present.

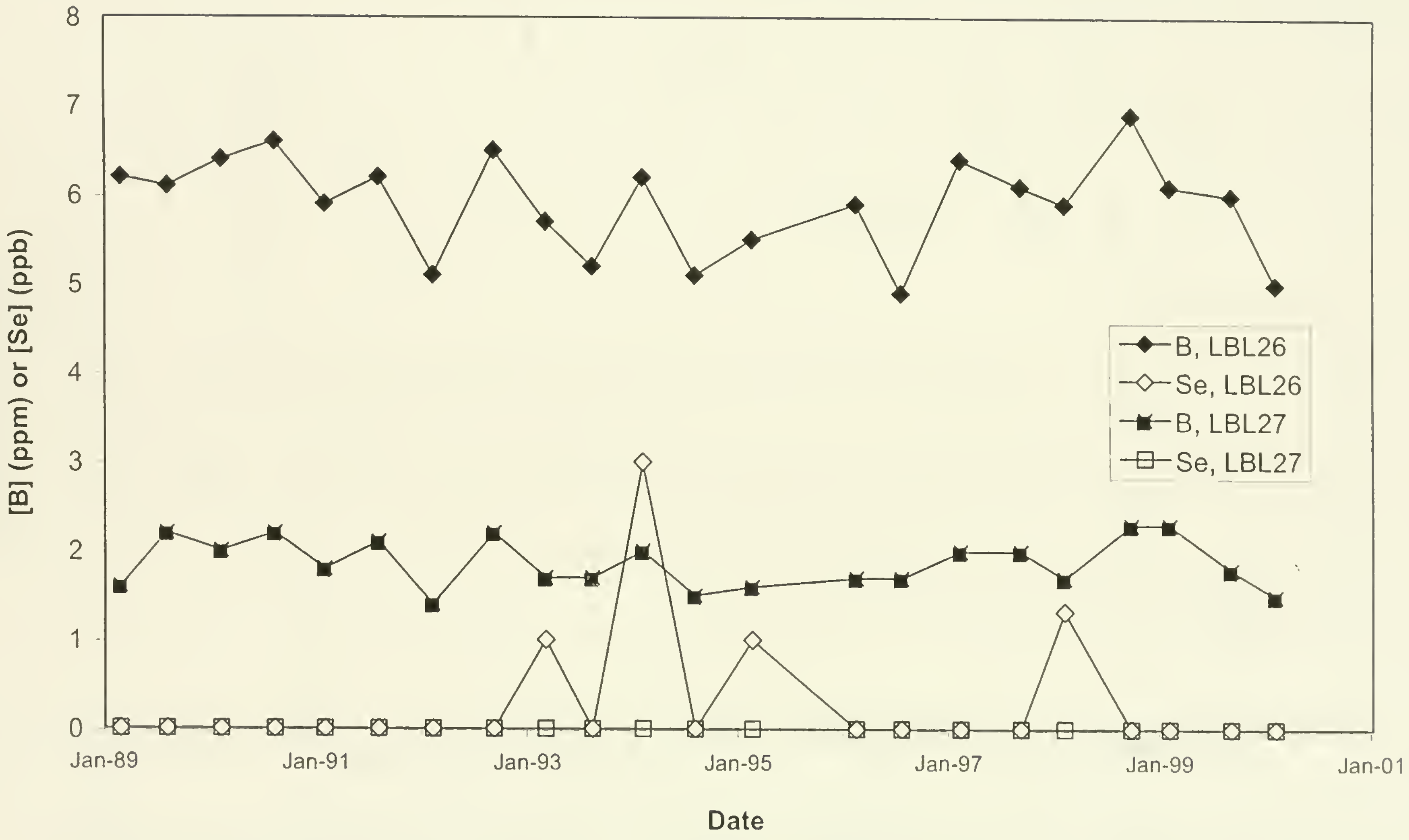


Figure A-4. Boron and selenium concentrations in groundwater from wells LBL26 and LBL27, 1989-2000.

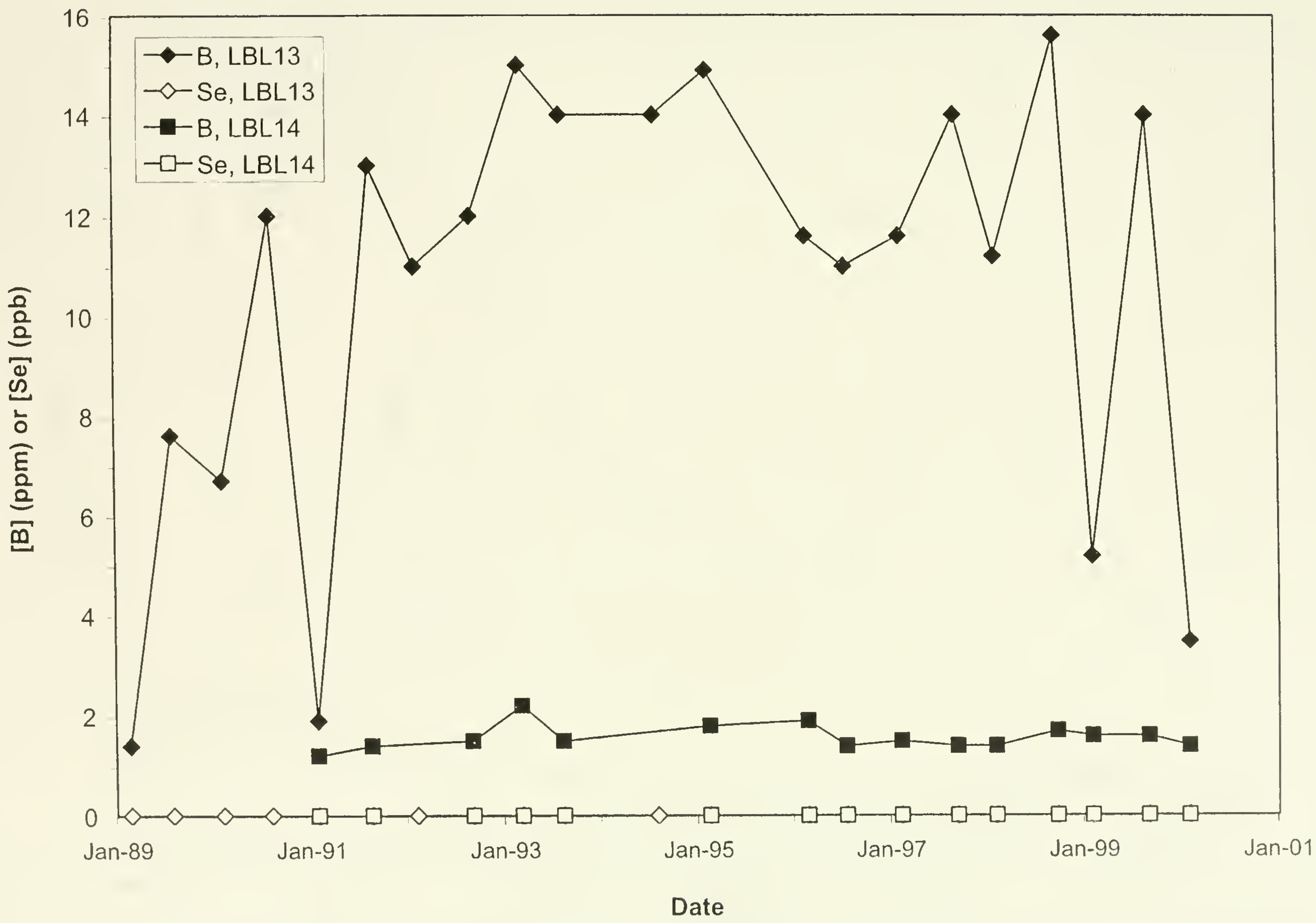


Figure A-5. Boron and selenium concentrations in groundwater from wells LBL13 and LBL14, 1989-2000.

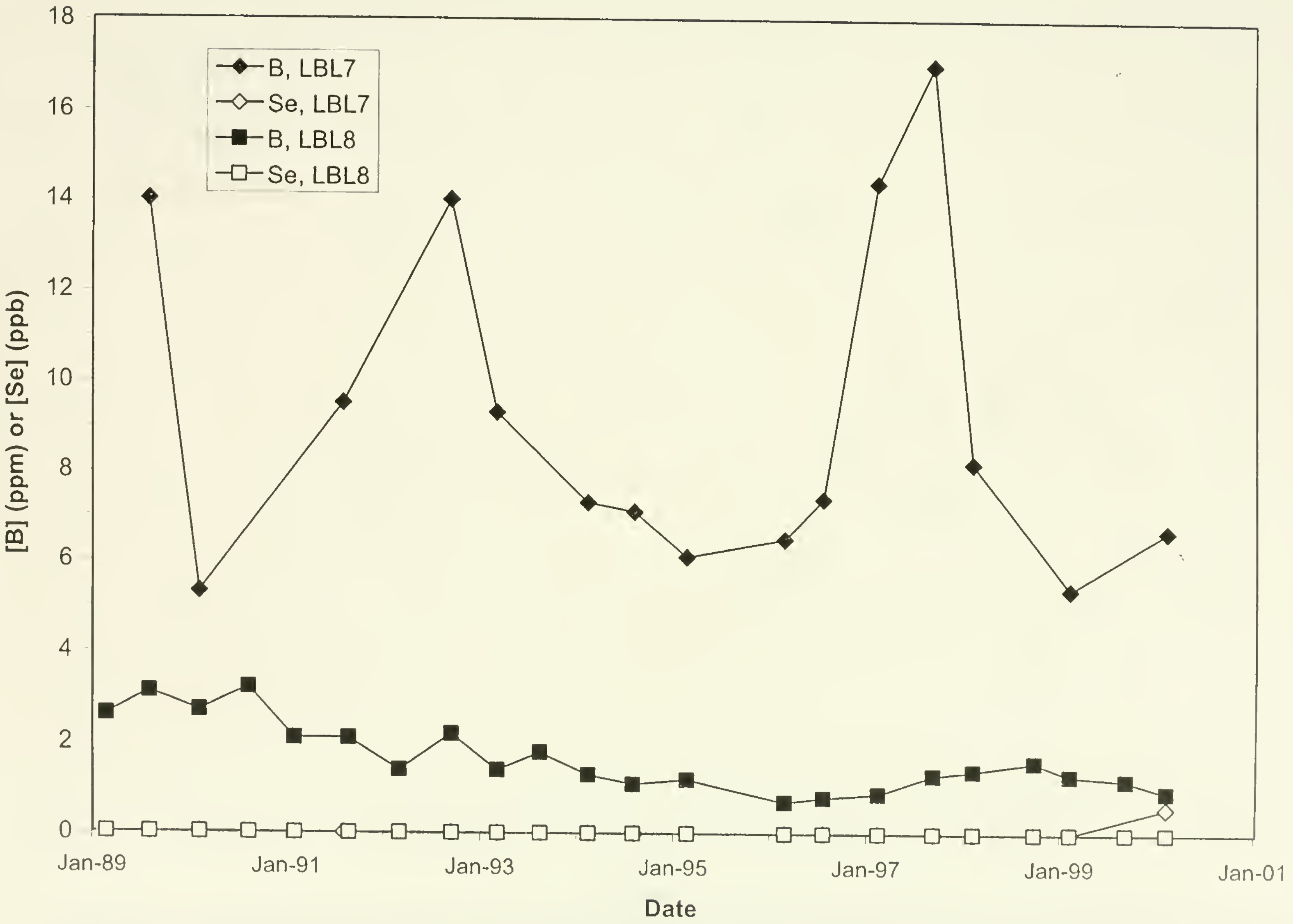


Figure A-6. Boron and selenium concentrations in groundwater from wells LBL7 and LBL8, 1989-2000.

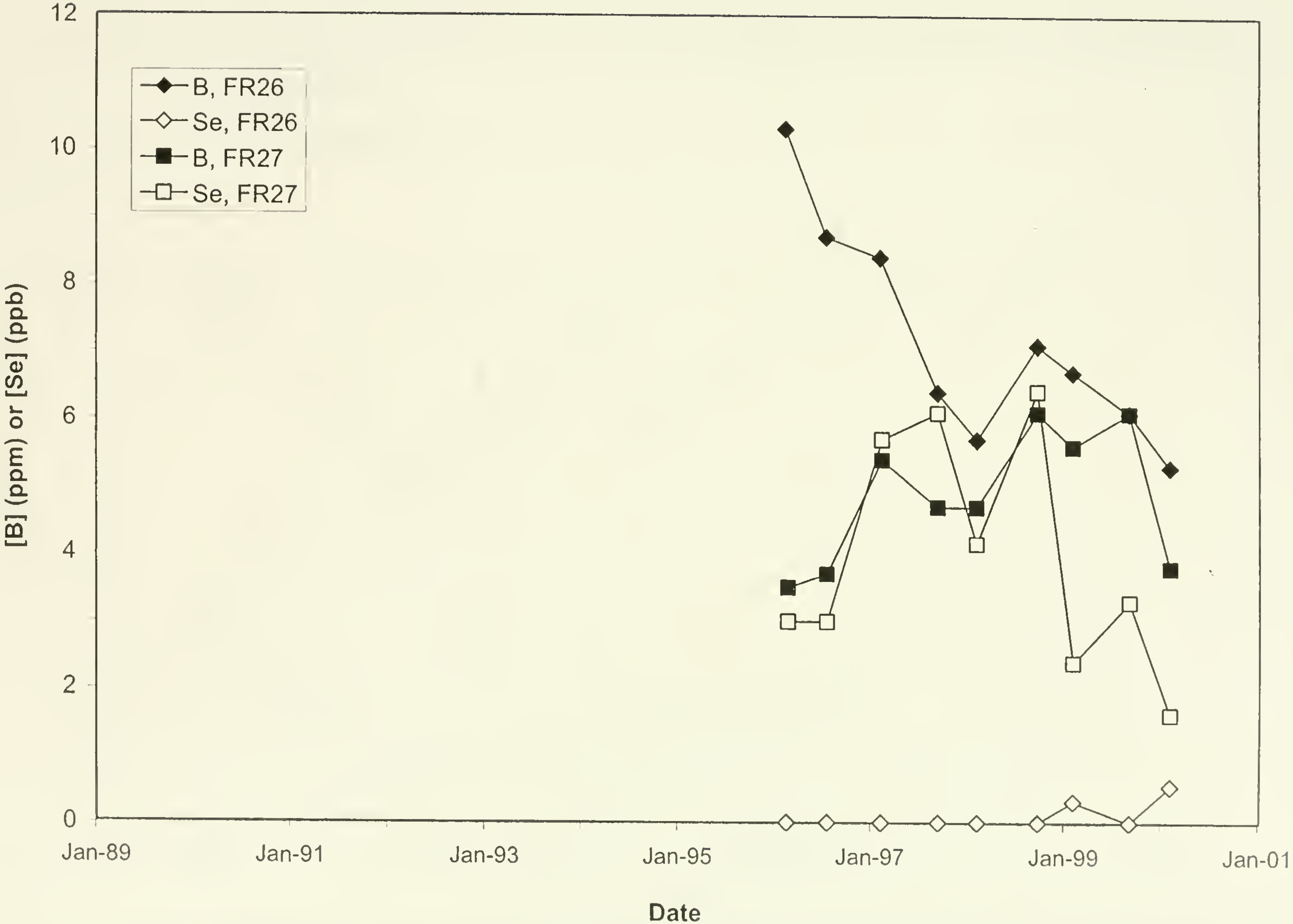


Figure A-7. Boron and selenium concentrations in groundwater from wells FR26 and FR27, 1996-2000.

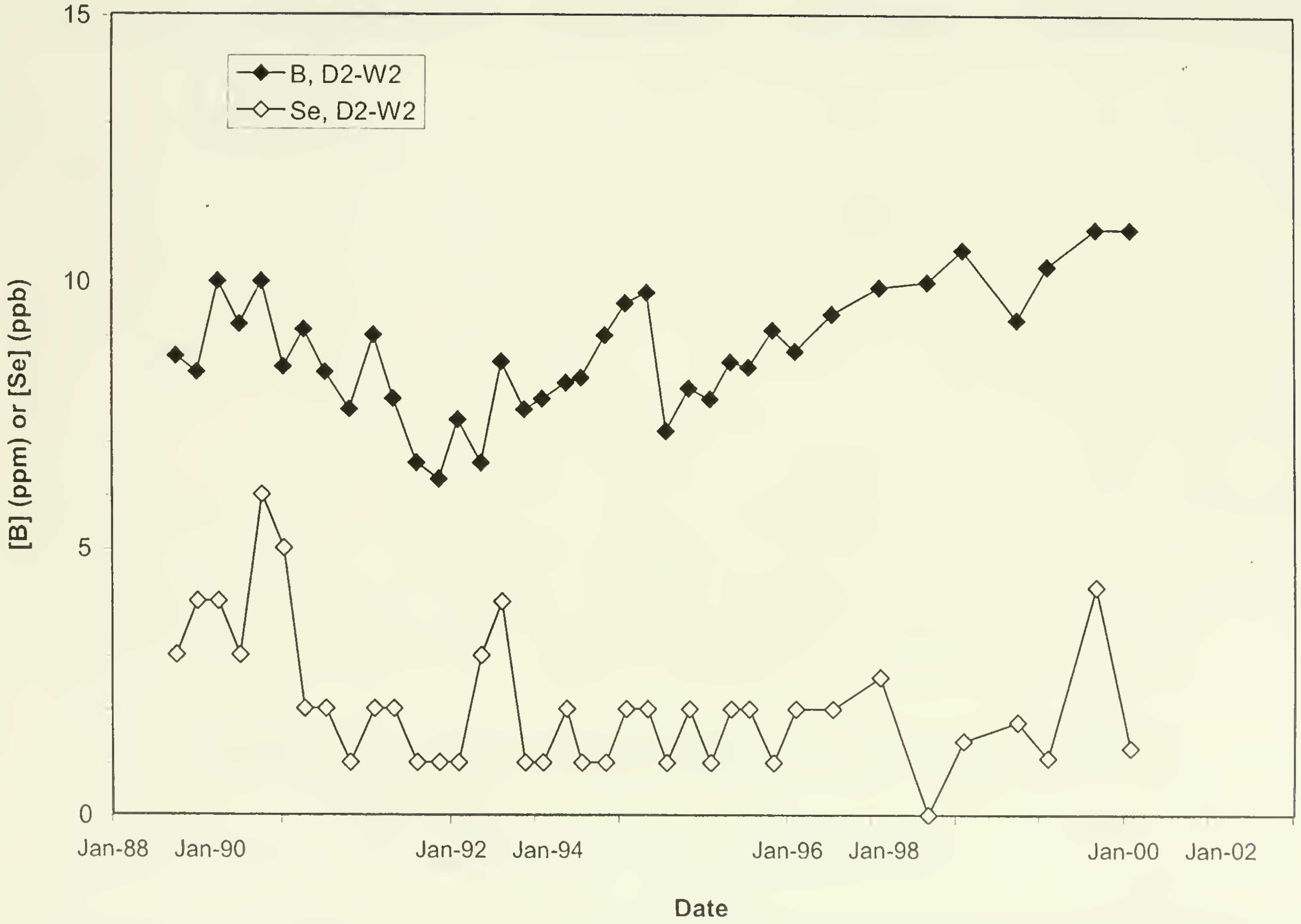


Figure A-8. Boron and selenium concentrations in groundwater from well D2-W2, 1989-2000

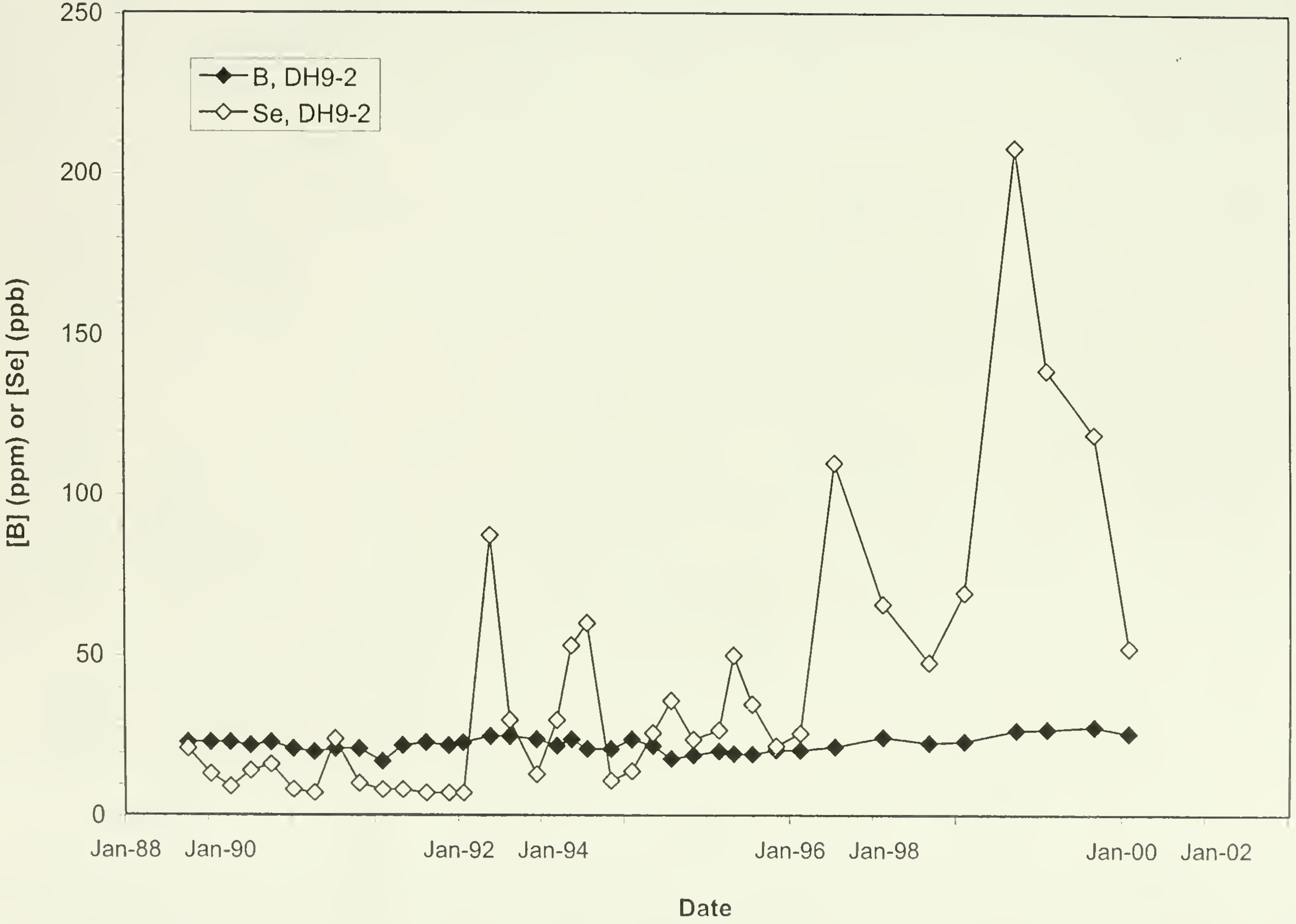


Figure A-9. Boron and selenium concentrations in groundwater from well DH-9-2, 1989-2000

Appendix B

Table B-1. Cumulative monthly rainfall (mm), relative to November 1st of the previous calendar year. 1874-1984 data are from Los Banos, CA. 1985-2000 are from Kesterson Reservoir.

water "year"	Nov 30	Dec 31	Jan 31	Feb 28	Mar 31	Apr 30	May 31	Jun 30	Jul 31	Aug 31	Sep 30	Oct 31	year total
1874	37	56	97	124	155	174	181	185	185	185	185	192	192
1875	25	60	154	154	163	177	178	180	186	186	186	186	186
1876	129	139	177	216	257	260	260	260	260	260	260	261	261
1877	4	4	28	35	39	39	40	40	40	40	40	40	40
1878	20	37	102	181	212	227	227	227	227	227	227	233	233
1879	5	12	25	47	58	75	80	82	82	82	82	85	85
1880	17	37	43	64	71	113	121	121	121	121	121	121	121
1881	15	102	127	156	178	203	203	203	203	203	203	203	203
1882	8	13	31	43	101	109	109	109	109	109	121	138	138
1883	14	16	57	68	114	116	162	162	162	162	162	173	173
1884	2	11	47	126	201	246	273	307	307	307	307	333	333
1885	1	102	123	125	141	160	160	160	160	161	161	161	161
1886	158	176	260	262	295	332	332	332	332	332	332	343	343
1887	5	10	11	50	61	72	72	72	72	72	72	72	72
1888	1	20	67	68	102	102	107	107	107	107	123	123	123
1889	76	125	132	151	196	201	218	218	218	218	221	243	243
1890	62	202	281	308	327	327	336	336	336	336	368	368	368
1891	4	38	39	94	104	146	146	146	146	146	151	154	154
1892	3	80	83	110	154	176	199	199	199	199	199	204	204
1893	18	86	105	161	217	221	224	224	224	224	226	227	227
1894	8	32	78	116	116	116	143	157	157	157	176	188	188
1895	3	107	187	212	243	252	261	261	261	261	261	266	266
1896	11	37	147	147	162	176	186	186	189	189	189	213	213
1897	27	40	68	113	144	144	144	144	144	146	146	166	166
1898	0	0	39	53	71	71	88	88	88	88	90	99	99
1899	1	18	59	59	110	139	139	139	139	139	139	193	193
1900	24	46	76	76	86	114	170	170	170	170	170	179	179
1901	95	109	155	205	211	238	280	280	280	280	280	292	292
1902	40	40	65	140	149	154	187	187	187	187	187	189	189
1903	25	32	71	91	159	159	159	159	159	159	159	159	159
1904	19	28	35	66	73	99	99	99	99	103	131	149	149
1905	6	30	96	141	213	220	254	254	254	254	254	254	254
1906	25	48	86	133	262	287	336	336	336	336	336	336	336
1907	31	118	198	228	340	340	352	366	366	366	366	389	389
1908	0	54	102	133	144	146	150	150	150	150	150	155	155
1909	21	47	173	237	280	280	280	280	280	280	280	285	285

water "year"	Nov 30	Dec 31	Jan 31	Feb 28	Mar 31	Apr 30	May 31	Jun 30	Jul 31	Aug 31	Sep 30	Oct 31	year total
1910	18	101	160	168	214	219	219	219	219	219	226	233	233
1911	7	15	136	168	243	252	253	253	253	253	253	253	253
1912	2	19	62	62	102	150	153	153	153	153	154	156	156
1913	7	7	54	72	89	98	109	109	114	114	114	114	114
1914	58	98	248	283	294	320	321	321	321	321	321	340	340
1915	5	56	106	169	193	219	258	258	258	258	258	258	258
1916	0	58	196	252	291	305	305	305	305	305	311	329	329
1917	10	73	105	138	149	161	166	166	166	166	168	168	168
1918	13	20	31	104	185	185	185	185	185	185	209	216	216
1919	32	81	90	125	155	157	157	157	157	157	183	192	192
1920	0	34	39	80	141	150	150	152	152	152	160	202	202
1921	54	97	172	185	216	254	254	254	254	254	255	257	257
1922	17	144	206	275	320	328	341	341	341	341	341	345	345
1923	60	98	125	139	139	198	200	202	202	202	210	211	211
1924	6	15	46	49	76	80	84	84	84	84	84	93	93
1925	24	66	84	104	117	149	201	201	201	203	204	206	206
1926	7	25	53	87	92	122	122	122	122	122	122	127	127
1927	57	76	95	159	191	198	198	204	204	204	204	219	219
1928	21	33	37	66	103	114	115	115	115	115	115	115	115
1929	53	99	140	167	176	191	191	205	205	205	205	207	207
1930	0	12	63	107	134	153	156	156	156	156	157	159	159
1931	17	17	71	94	112	118	133	136	136	137	137	137	137
1932	41	130	167	207	237	244	250	251	251	251	251	251	251
1933	1	23	95	101	117	117	125	126	126	126	126	130	130
1934	0	64	93	134	134	135	136	141	141	141	141	151	151
1935	41	88	148	158	210	270	270	270	270	272	272	278	278
1936	25	50	64	190	219	235	239	240	241	241	241	265	265
1937	0	61	97	151	226	237	237	237	237	237	237	238	238
1938	12	72	124	225	311	325	326	326	327	327	330	360	360
1939	1	21	36	63	88	105	107	107	107	107	127	130	130
1940	3	10	118	196	224	241	241	241	241	241	241	258	258
1941	1	99	162	244	311	359	359	359	359	360	360	389	389
1942	17	70	108	139	160	222	237	237	237	237	237	245	245
1943	9	33	68	89	176	190	190	190	191	191	191	196	196
1944	9	42	78	129	138	163	172	174	174	174	176	183	183
1945	43	72	79	119	174	178	182	182	182	183	183	258	258
1946	40	87	98	125	136	138	166	166	166	166	167	180	180
1947	59	99	106	134	154	159	167	169	169	169	170	194	194
1948	13	23	23	44	91	160	183	183	183	183	183	194	194
1949	0	36	55	82	135	135	160	160	161	161	161	161	161

water "year"	Nov 30	Dec 31	Jan 31	Feb 28	Mar 31	Apr 30	May 31	Jun 30	Jul 31	Aug 31	Sep 30	Oct 31	year total
1950	33	62	108	130	144	162	163	163	163	163	178	199	199
1951	35	71	95	120	134	147	147	147	147	147	148	163	163
1952	39	115	202	214	265	313	313	314	314	314	318	318	318
1953	32	104	115	115	120	145	150	151	151	151	151	151	151
1954	24	29	71	98	148	168	175	175	175	175	175	175	175
1955	34	70	141	160	166	188	210	211	211	211	211	212	212
1956	19	158	234	241	241	275	289	289	289	289	293	299	299
1957	0	4	49	83	125	145	175	179	179	179	181	208	208
1958	5	50	115	208	311	359	366	367	367	367	379	379	379
1959	2	9	52	118	121	131	131	131	131	132	166	166	166
1960	0	10	46	114	127	153	153	153	153	153	155	155	155
1961	57	62	103	124	153	158	174	174	174	175	175	175	175
1962	38	69	106	240	259	259	259	259	259	259	259	264	264
1963	3	42	82	170	204	250	255	258	258	258	259	286	286
1964	31	34	51	51	73	85	85	95	95	95	101	169	169
1965	27	98	117	126	145	198	198	198	198	205	205	207	207
1966	123	162	180	200	202	207	215	215	219	219	220	220	220
1967	42	116	169	177	206	283	285	287	287	287	287	289	289
1968	34	60	82	112	140	145	148	148	148	148	148	161	161
1969	42	89	208	315	325	344	344	344	344	344	382	419	419
1970	18	36	112	126	158	159	159	159	159	159	159	168	168
1971	57	108	121	130	145	164	189	189	189	189	190	197	197
1972	18	57	68	74	74	80	80	81	81	81	83	98	98
1973	127	149	221	313	350	351	351	351	351	351	352	382	382
1974	29	82	123	131	180	194	194	194	205	205	205	227	227
1975	11	65	69	139	185	210	210	210	211	217	217	243	243
1976	2	6	10	38	49	75	75	77	77	96	146	168	168
1977	19	38	56	64	73	73	100	106	106	106	108	112	112
1978	7	72	177	265	367	409	412	412	412	412	420	420	420
1979	34	46	104	172	229	233	238	238	239	239	239	255	255
1980	18	35	108	187	216	228	235	235	235	235	235	236	236
1981	0	12	55	81	154	173	173	173	173	173	173	191	191
1982	76	93	134	166	252	290	290	293	293	293	310	331	331
1983	66	103	198	253	347	378	382	382	382	385	455	466	466
1984	54	121	124	146	154	156	156	157	157	157	157	175	175
1985	64	104	119	128	156	157	157	161	161	161	161	173	173
1986	74	109	137	232	305	316	318	318	318	318	329	330	330
1987	0	12	57	105	177	180	184	184	184	184	184	196	196
1988	21	91	142	156	159	204	215	217	217	217	217	218	218
1989	30	72	93	126	159	162	163	163	163	164	203	222	222

water "year"	Nov 30	Dec 31	Jan 31	Feb 28	Mar 31	Apr 30	May 31	Jun 30	Jul 31	Aug 31	Sep 30	Oct 31	year total
1990	17	26	71	113	132	139	181	181	181	181	181	183	183
1991	4	24	31	86	190	202	206	209	209	211	211	231	231
1992	7	37	68	219	293	296	296	298	301	301	301	319	319
1993	9	64	188	291	355	361	385	393	393	393	393	394	394
1994	21	48	105	193	203	243	281	281	281	281	282	295	295
1995	30	55	198	212	322	344	359	363	364	364	364	364	364
1996	4	74	148	243	292	320	362	365	365	365	365	396	396
1997	42	148	233	234	234	244	244	244	244	244	244	244	244
1998	27	61	124	320	374	399	487	489	489	489	490	537	537
1999	33	47	86	124	162	177	178	178	178	178	179	179	179
2000	18	22	98	179	190	223	226						226

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